Dynamic Performance: Assessing Cabling Claims for 10GBASE-T

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DATA COMMUNICATIONS COMPETENCE CENTER

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Abstract

Claims by cabling manufacturers of 10GBASE-T support are becoming commonplace. It is very difficult for consultants, contractors and end-users to sort through the hype and understand the real and very complex issues regarding 10GBASE-T and modern LAN cabling. This makes the job of specifying cabling to support this emerging application very challenging and somewhat risky.

This white paper looks at the technology challenges of designing and manufacturing copper LAN cabling to ensure robust support for modern communication systems including 10GBASE-T. You will see that it is imperative that cabling solutions form an integral part of any communication system and that they are designed to complement the rapidly evolving, active electronics to which they connect.

Many cabling companies seem to be presenting a biased view of 10GBASE-T issues and challenges in order to minimize the perceived complexity or to market new or emerging UTP cabling solutions. The fact is that the IEEE 802.3an standardization process is in its early stages and there is no draft document to reference. The cabling requirements needed to ensure robust operation over a 100-meter, four-connector UTP cabling channels are neither specified nor known at this time and cannot be finalized without consensus on key decisions regarding signaling scheme, equalization, latency, DSP noise reduction and error correction. Even when these decisions have been made, the robustness of a UTP solution, when installed in the real world, will not be known until more investigation has been made regarding real-world variables such as elevated temperature, humidity changes, external noise sources and installation imperfections. In addition, simulations have shown that the alien crosstalk from nearby UTP cables is a dominant noise source for UTP cabling that prevents current-generation category 6 solutions from reliably operating under worst-case conditions.

History has shown that cabling technology evolves at a rapid pace as does digital signal processing (DSP) and integrated circuit technology. When the requirements for robust operation over UTP are developed and well-understood, UTP cabling technology will be developed or refined to meet the challenge of 10GBASE-T over 100-meters. However, until these issues are resolved, it is recommended that you consider shielded solutions such as an FTP (foil-shield, twisted-pair) or a category 7 cabling solution if 10GBASE-T support must be ensured. Both Category-6 FTP and category 7 shielded solutions exist today that offer robust performance over the frequencies needed for 10 Gb/s operation without significant alien crosstalk. Shielded cables are the only twisted-pair cables that have industry consensus as having adequate capacity for 100-meter operation. It is premature to assume that any existing UTP system will offer robust, 100-meter operation of 10GBASE-T under

real-world conditions. Network and Infrastructure designers and consultants need to design for worst-case and not best-case scenarios.

Introduction

The IEEE is currently developing a standard for next-generation Ethernet over copper twisted-pair LAN cabling. This has generated a tremendous amount of interest in both the cabling and local area network (LAN) industries as cabling and active equipment manufacturers scramble to develop technology to support this emerging application concurrent with the standardization process, which is still in the early stages.

The IEEE approved the P802.3an project in early 2004 and held its first task force meeting in March 2004 in Orlando, Florida. However, work within the IEEE started almost eighteen months earlier (in November 2002) with a call-for-interest for 10GBASE-T and the formation of an IEEE study group that was tasked to develop and justify a project authorization request.

More than a year before the IEEE call for interest, Nexans began development of copper cabling systems designed to operate at data rates of 10 Gb/s in anticipation of the eventual standardization process. Working with Pennsylvania State University's Center for Information & Communications Technology Research (CICTR) and funded by the International Copper Association (ICA), a method and system for implementing 10GBASE-T in the presence of noise was developed, simulated and presented[1] to the IEEE 10GBASE-T study group during the November 2003 meeting to help demonstrate the feasibility of running 10 Gb/s over copper cabling at 100-meters.

The work by CICTR researchers has resulted in several exciting discoveries:

- Confirmation of the feasibility of 10GBASE-T over category 6 cabling systems at 100-meters. During this time, there was considerable debate over the viability of 10GBASE-T over copper LAN cabling.

- Refinements to the decision feedback equalizer (DFE) technology currently used in current Ethernet applications over copper (e.g. 1000BASE-T). Although DFE is currently used to mitigate dispersion in the channel, this new technology, called Survivor Path Feedback Equalization, along with 4-D TCM (Trellis Code Modulation) can achieve an error rate of 10^{-12} at 10 Gb/s transmission over 100-meters of a standard CAT-6 cabling. This assumes an optimistic level of alien crosstalk as specified currently by IEEE[2] in the baseline link segment models.

- In the event that actual, real-world alien crosstalk is somewhat more pessimistic than assumed, more powerful schemes, such as Turbo Equalization, can be employed to meet the desired bit error rate (BER) performance. This will result in a more complex and costly transceiver, but would make the task of running 10GBASE-T over UTP easier by being more tolerant to external noise.

- If the alien crosstalk is substantially worse than the current IEEE link model[2], such as presented by Broadcom[3], Vativ and Marvell to the IEEE study group in May 2003, then no known code will achieve the target performance level over 100-meters of category 6 UTP cabling.

These conclusions regarding the ability of UTP cabling to support 10GBASE-T in the presence of various levels of alien crosstalk are at the center of the uncertainty and disagreement in the industry regarding cabling solutions to support this application in real-world installations. Accurate prediction of the noise environment in the field and the subsequent performance of the cabling are far from a certainty for UTP cables.

Concurrent with the development of the 10GBASE-T simulation tools and system models, Nexans has been conducting research and development relating the balance of the cabling to the immunity of the system to external noise from a variety of electrical and electromagnetic sources, including alien crosstalk. Cabling balance, relates to the consistency and quality of the manufacturing processes of cables and cabling components. However, it is not adequately specified in existing cabling standards so robust operation of today's applications such as 10GBASE-T are not ensured. Substantial work in standardization remains to strengthen these specifications to provide true value to the end user.

The data rate of modern LAN applications has increased to the point that the capacity of copper cabling is being taxed. In order to achieve gigabit and multi-gigabit data rates on four-pair copper cabling, extremely complex digital signal processing is employed. It has become necessary for customers to look at the channel capacity of cabling in conjunction with the abilities, strengths and weaknesses of the active electronics necessary for the system to operate. Simplistic estimations of capacity such as ACR (attenuation-to-crosstalk ratio) no longer apply to modern applications due to this complexity. Even a traditional capacity calculation based on Shannon's Law has become less useful since it can oversimplify the assumptions and lead to overly optimistic or overly pessimistic estimations of capacity. Modern cabling systems need to be designed and developed using modern methods including simulation tools such as those described in this paper. This allows more accurate estimations of the capacity of real-world cabling plants, facilitating growth planning, asset management and realistic expectation levels.

10GBASE-T Standardization Update

Work has started on 10GBASE-T, 10 Gigabit/second Ethernet over copper LAN standard. In the first quarter of 2004, the IEEE Standards Association approved the project approval request[4] (PAR) of the IEEE 802.3 10GBASE-T Study Group. The resulting task force, IEEE P802.3an, held its first meeting March 15-18, 2004 in Orlando, Florida.

The following cabling objectives were among the objectives[5] agreed by the 10GBASE-T study group for P802.3an during the September 2003 meeting:

- To support operation over 4-connector, 4-pair, twisted-pair copper cabling channels for all supported distances and cabling classes (categories).
- To define a single 10 Gb/s physical layer (PHY) that would support links of:
    - At least 100 m on four-pair, Class F (category 7) cabling
    - At least 55 m to 100 m on four-pair, Class E (category 6) cabling
- To support a bit-error-rate (BER) of 10^{-12} on all supported distances and cabling classes (categories).

To achieve the cabling objectives agreed to in September 2003, members of the working group negotiated basic requirements for electrical channel models to be used as a starting point. TIA TR42 and ISO/IEC JTC1/SC25/WG3 have been asked to refine these models and provide feedback to IEEE 802.3. Ultimately, the IEEE task group will use the completed models in the development of the 10GBASE-T standard. During the first P802.3an meeting, held in March 2004, the task force adopted four, baseline link segment models[2] for alien near-end crosstalk each based on different cabling categories and length objectives:

Model	Insertion Loss	Alien Near-end Crosstalk at 100 MHz
1	100-meters Class F (Category 7)	60 dB
2	55-meters Class E (Category 6)	47 dB
3	100-meters Class E (Category 6)	62 dB
4	By Formula (55 to 100 meters Category 6)	Prorated calculation (Based on Insertion Loss)

Table 1: IEEE P802.3an Cabling Objectives for Baseline Link Model

As can be seen in table 1, the first and third models are the two applicable models designed to support 100-meter cabling channels as allowable in horizontal spaces in TIA or ISO structured cabling standards. Model 1 is based on category 7 cabling channels whereas model 3 is based on category 6 FTP (foil-shielded, twisted-pair) cabling channels. Conforming to one of these two models with 100-meter UTP cabling channels is a necessary first step in developing an augmented category 6 UTP cabling specification.

It is anticipated that operating over 100-meters of UTP category 6 will require substantial augmentations to existing category 6 specifications. This will eventually result in a new enhanced category-6 cabling standard specifically designed for 10GBASE-T transmission.

The proposals contain specifications for alien crosstalk. Alien crosstalk is a critical cabling parameter because it is too difficult for the electronics to cancel without adding enormous cost and complexity to the design of the transceiver. It is important to specify alien crosstalk for both near-end and far-end disturbers. Currently, the standardization process is focused on near-end disturbers. Models similar to those in table 1 do not exist for alien far-end crosstalk. Since adjacent cabling channels in a typical LAN installation are not the same length, the far-end disturbing transmitters may be much closer to the victim receiver than the victim's far-end transmitter, effectively amplifying the noise. Because of this, alien far-end crosstalk may prove to be the more difficult challenge for cabling. While power back off is an option for the shorter, disturbing channels, that will reduce the alien far-end crosstalk in the longer disturbers, this technique may make these short channels more susceptible to alien near-end crosstalk.

Current performance specifications for category 6 cover frequencies from one to 250 MHz. TIA TR42 and other cabling standardization committees are providing cable and channel performance data for frequencies up to 625 MHz. Most solutions that have been proposed to the IEEE 10GBASE-T study group require a cabling bandwidth between 400 and 500 MHz.

System Performance

Years ago, when 10BASE-T (10 Mb/s Ethernet over twisted-pair) was a cutting-edge LAN application, the signal-to-noise ratio at the receiver was estimated by using the attenuation-to-crosstalk ratio (ACR) of the cabling. Actually, the attenuation-to-crosstalk of the cable itself was used since this pre-dated the link and channel specifications found in today's cabling standards. The attenuation-to-crosstalk ratio was a sufficient metric for signal to noise ratio (SNR) because there was so much crosstalk present in early twisted-pair cables that the noise was dominated by the crosstalk from the sole, near-end transmitter. The interactions between the cable and the connecting hardware were relatively small such that matching between the cable and the connecting-hardware components was not considered significant.

With the commercialization of Category 5, and eventually Category 5e cabling systems, near-end crosstalk and other electrical performance parameters were improved to the point where the interaction between the cable and connecting hardware became very significant. Link and channel specifications were created to quantify this interaction in order to provide channel performance specifications to network electronics designers. Crosstalk was still considered to be the dominant noise source, and the attenuation-to-crosstalk ratio of the channel became a key performance metric.

With the emergence and proliferation of digital technology in LAN transceivers, today's situation is much different. Digital signal processing (DSP) has become so cost effective that very complex algorithms are routinely employed in modern LAN transceivers. Using DSP, both near-end and far-end crosstalk can be substantially cancelled even when considering multiple transmitters that are employed by today's applications. Thus ACR is no longer an accurate or applicable indication of the signal-to-noise. Today's twisted pair cables and cabling channels, such as category 6, contain only a small fraction of the crosstalk energy that older versions had. Because of this, and because modern applications use much higher symbol rates and more complex signaling schemes, other noise sources, such as alien crosstalk and ambient electrical and electromagnetic noise, have become much more significant. Moreover, interaction between the passive components in the channel and the active transceivers has become important.

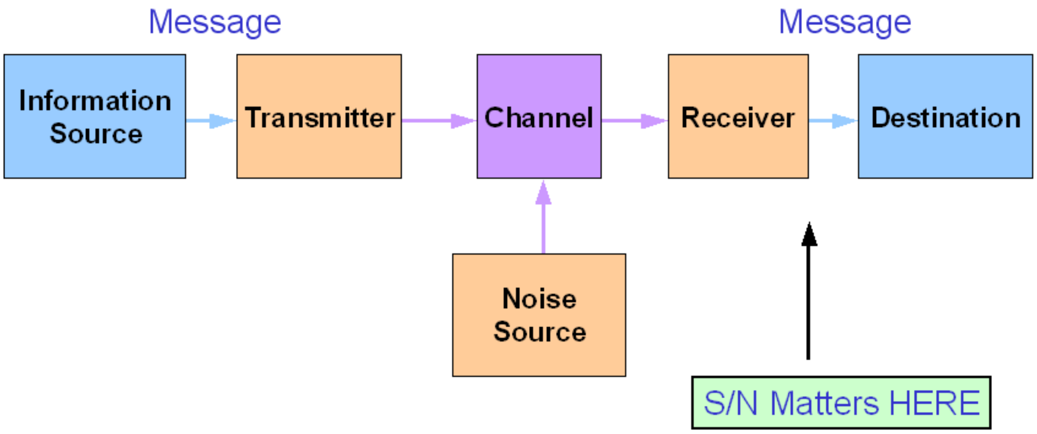

Figure 1: Block Diagram of Communication System

As shown in figure 1, adapted from Figure 1 of Claude Shannon's 1948 paper[6], "A Mathematical Theory of Communication", the passive cabling channel forms only one part of the communication system. The signal-to-noise ratio is critical at the point in the receiver where the decision is made as to what bit or symbol was intended. All system components play a role in determining the received SNR including noise from sources external to the communication system.

It becomes quite a challenge, considering the complexity of the noise environment, signaling scheme and digital signal processing to design a cabling system that will maximize the signal-to-noise ratio at the receiver for modern LAN applications.

It is a confusing and daunting task to sort through all the "marketing hype" to determine what will improve the network's reliability and performance and what will be important to ensure robust performance for tomorrow's applications such as 10GBASE-T. Improvement to network reliability and robustness is a key goal because it will improve the bottom line through a lowered cost of ownership.

To help sort through the confusion, we need to return to Claude Shannon's now-famous communication theory. As shown in Figure 2, Shannon's Law, in its simplest form, relates channel capacity to signal-to-noise across the usable bandwidth of the communication channel.

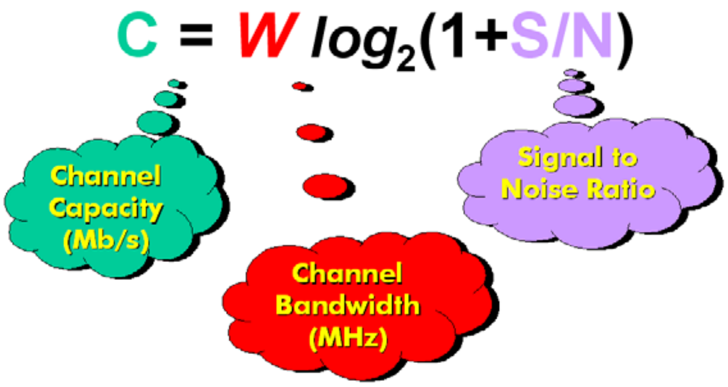

Figure 2: Shannon's Law in Simplest Form

What Channel Capacity Means

Channel capacity is very important because it tells us the maximum data rate (bits of information per second) that can be transmitted from the source to the destination without error. This remains true even when the transmission channel is noisy, provided the bandwidth and received signal-to-noise requirements are met.

However, this does not mean that there will never be a bit error nor does it mean that the bit error rate is zero. Since there is always a chance that any given bit will be erroneous, the bit error rate will always be greater than zero. What it does mean is that codes exist that allow systems to be designed such that the average probability of a bit error is sufficiently small.

When a digital communication system operates at a data rate that is greater than the channel capacity, there will be a high probability of error. Thus, it is very important to have a sufficient signal-to-noise ratio for the application to ensure reliable and trouble-free operation under actual, real-world operating conditions. It is also very important to have sufficient bandwidth to ensure that the network application you are intending to run operates within the channel's capacity.

Limitations of Channel Capacity

The channel capacity, as calculated using Shannon's Law and other variations, can be misleading if not carefully used and interpreted. As previously stated, it represents the maximum data rate in which digital communication can reliably take place. It does not, however, indicate the practicality or manufacturability of the digital communication system. Just because codes exist to obtain the data rate does not mean that it would be practical to manufacture a transceiver to send and receive them. Nor does it have any provision to ensure that the resulting equipment would have a palatable price tag or have a power consumption that allows packaging for use in a conventional switch or network interface card (NIC).

With that in mind, it is important that appropriate assumptions are made when calculating the channel capacity of a digital communication system. This ensures that practical implementations would be able to offer robust operation under a variety of real-world operating conditions. This can be accomplished by carefully choosing the proper noise sources and levels ensuring that communications systems are designed for real-world networks.

Although today's integrated circuits are extremely powerful, they do have limits on complexity and speed. Fortunately, semiconductor and active equipment providers are constantly pushing this envelope. As the cancellation, error-correction, adaptive equalization, wave shaping and other DSP techniques improve, the maximum, practical channel capacity will naturally improve, always bounded by the ultimate theoretical capacity.

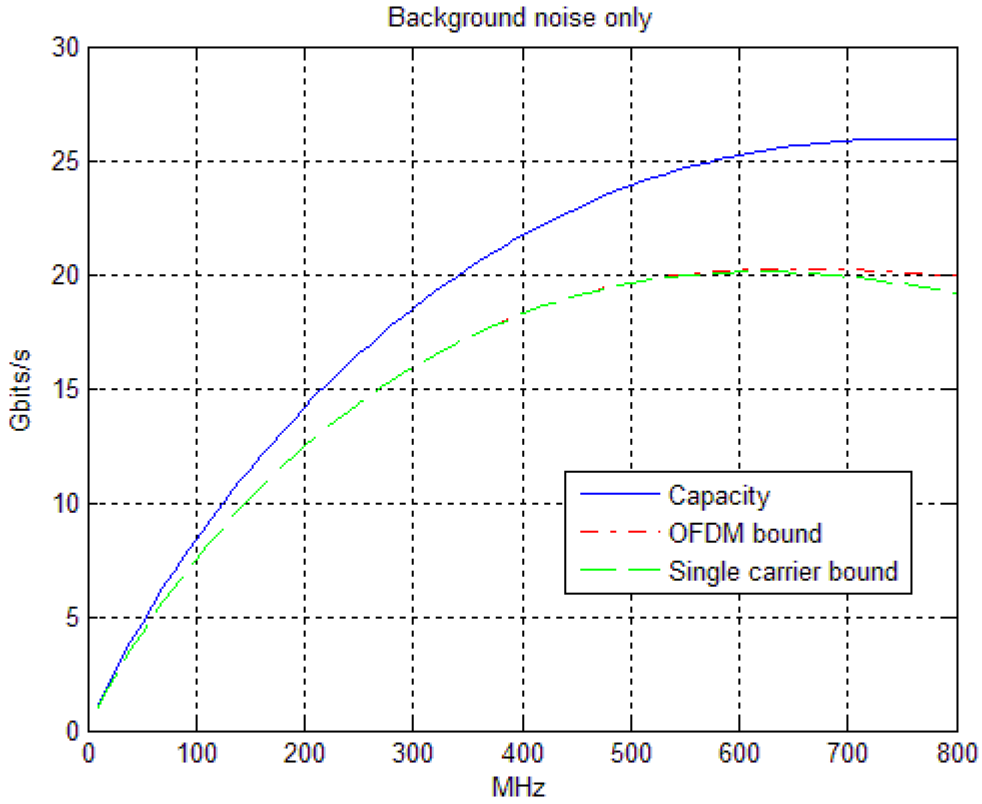

Figure 3: Channel Capacity Example

Figure 3 shows the channel capacity of a UTP category 6 channel assuming only background noise. Even with this simple model, you will note the differences between the different capacity calculations, especially at higher frequencies (> 400 MHz) where 10GBASE-T will operate. In this case, the capacities were computed using an AWGN (average white Gaussian noise) of –150 dBm/Hz. At the frequencies where 10GBASE-T will likely operation (up through 400 to 500 MHz), substantial differences are seen between an unbounded Shannon capacity (upper line) and more realistic estimations that include coding restraints.

The most optimistic line (labeled capacity) represents the theoretical ideal under these noise conditions. The OFDM bound and Single Carrier Bound lines represent more realistic capacities based on specific modulation schemes. 10GBASE-T will most likely use a single carrier modulation scheme, so the Single Carrier Bound capacity is most appropriate for this application.

Figure 4 shows the channel capacity for the same UTP category 6 channel as in figure 3, however, the noise assumptions are somewhat different. Near-end crosstalk (NEXT), echo and far-end crosstalk noise have been added along with DSP cancellation of 60 dB, 34 dB and 76 dB, respectively. These cancellation levels have been determined through network simulation and have demonstrated the ability to achieve 10^{-12} BER over category 6 channel. Additionally, alien near-end crosstalk noise has been added without any cancellation. The alien crosstalk used assumed an optimistic level of alien crosstalk according to current IEEE channel models[2].

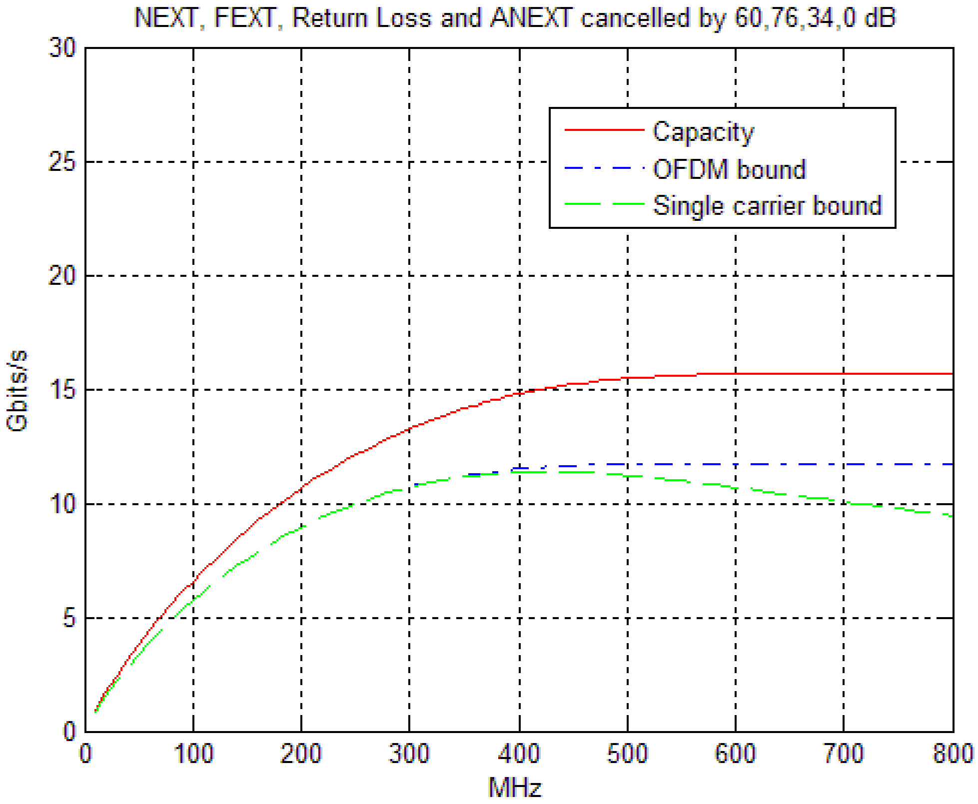

Figure 4: Another Capacity Example

As can be seen by comparing the capacities of figure 3 and figure 4, it is important to keep in mind that channel capacity calculations are always dependent on the assumptions made on the noise sources. It is very easy to inadvertently make apple-to-oranges comparisons when looking at the channel capacities of two different systems if the assumptions are not fully understood. You should challenge capacity calculations made by cabling manufacturers to fully understand what is assumed and what capacity is really being delivered. Oversimplification of the channel capacity calculations usually results in an overly optimistic view that can result in expectations for the cabling plant that cannot be met.

Bit Errors

Bit error rate is a quantitative measurement of the reliability of a digital communication system. The lower the bit error rate, the more reliable the communication system is. Market research (Sage Research, December 1998) has shown that improved network reliability is the most important driver of network upgrades for more than 80% of the IT managers that were surveyed. BER is an excellent metric for network reliability.

One way to express the probability of errors occurring at the receiver output is by the bit error rate (BER). The bit error rate can be estimated by counting the number of observed errors at the receiver as a ratio to the number of bits sent.

In the frame-oriented networks prevalent in data communications, this might not be possible. For example, many systems, like Ethernet, will discard the entire frame even if one bit is erroneous. Many copper-based systems (100BASE-TX and 1000BASE-T, for example) use multilevel coding (MLT-3, PAM-5) and block coding to effectively transmit multiple bits per symbol. In these systems, even if the contents of the frame could be examined, only the number of erroneous symbols could be detected and not individual bits.

To estimate the bit error rate in a frame-based system, the frame error rate is measured instead. A conservative approach is to assume that if a frame contains an error, all bits (or symbols) in the frame are in error. Consequently, the frame error rate equals bit error rate in this case. This also provides a worst-case estimation of bit error rate, ensuring adequate reliability. When evaluating claims regarding bit error rate, with frame-based applications, be sure to understand the assumptions. They can make significant differences in the meaning of advertised values and the subsequent value of the cabling system.

Cabling Challenges of 10GBASE-T

When considering the system and cabling requirements for 10GBASE-T solutions, it is necessary to consider all significant signaling impairments that will reduce the signal to noise ratio of the system. Without adequate signal-to-noise across the required channel bandwidth, reliable and robust 10GBASE-T performance will not be achieved. Adequate signal-to-noise must be achievable in real-world installations considering variables such as temperature, humidity, alien crosstalk and other external noise sources.

Table 2 shows a list of the significant signal impairments along with most likely mitigation technique. The challenge for cabling designers is to develop and manufacture cabling solutions that work synergistically with the active electronics to create a robust, yet economical 10GBASE-T solution.

Impairment	Mitigation Technique
Insertion Loss Dispersion	Channel Equalization using Tomlinson-Harashima (TH) Precoding or Decision Feedback Equalization (DFE)
Near-end Crosstalk (NEXT)	NEXT Cancellation
Far-end Crosstalk (FEXT)	FEXT Cancellation
Return Loss (Echo)	Echo Cancellation
Residual Noise/Insertion Loss	Error-correcting Channel Coding using low-density parity-checking (LDPC) code
Electromagnetic Interference (EMI)	Cable Design Improvements, Improvements to Cabling Balance
Alien Near-end Crosstalk	Alien Crosstalk Mitigation Techniques, Cable Design Improvements, Improvements to Cabling Balance Optionally use shielding
Alien Far-end Crosstalk	Alien Crosstalk Mitigation Techniques, Cable Design Improvements, Improvements to Cabling Balance Optionally use shielding

Table 2: Signal-to-Noise Impairments for 10GBASE-T

Table 3 summarizes the key challenges for 10GBASE-T and the respective challenges for the cable in order to enable robust operation over 100-meter, four connector channels. Although it is premature to know the exact requirements for cabling since critical decisions regarding signaling have not been made, this table is a useful tool to identify trends in cabling performance necessary to support modern network applications. As such, these challenges must be met by the passive cabling regardless of the signaling methods chosen.

10GBASE-T Challenge	Cabling Challenge
Alien Crosstalk is a dominant noise source. It is very difficult to cancel, potentially adding cost and complexity to transceiver.	Improve balance and reducing insertion loss of cabling to minimize the amount of Alien Crosstalk mitigation needed.
Electromagnetic Interference (EMI) is another noise source that needs to be mitigated.	Improving balance and reducing insertion loss to reduce the amount of external noise coupled onto the cabling.
Proposals seen to date will use bandwidth well beyond the 250 MHz that is specified for Category 6.	High-frequency characterization of cabling performance to frequencies well above 250 MHz. Ensure that material properties and manufacturing processes are adequate.
Possible performance tradeoffs versus link length.	Characterization of length dependency of cabling links/channels that may not follow a linear relationship.
Launch power is limited due to need to conform to FCC regulations and meet power restrictions based on transceiver packaging.	Improve cabling insertion loss to minimize degradation of signal power.

Table 3: Cabling Challenges for 10GBASE-T

High-frequency characterization

During the development of the project authorization request, five criteria and objectives to justify the 10GBASE-T project, the IEEE 802.3 10GBASE-T study group developed models based on scaled data measured to 625 MHz. Figure 5 shows an example of measured insertion loss of a commercially available, four-connector, 100-meter category 6 channel. At frequencies below 500 MHz, the measured data performs better than the model. However, the model is optimistic at higher frequencies.

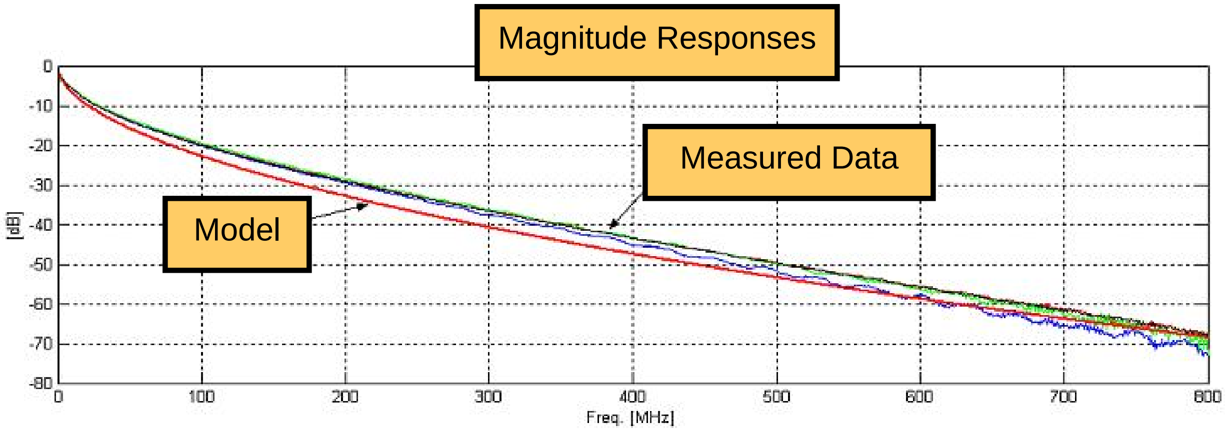

Figure 5: Comparison of measured insertion loss to IEEE model

From the insertion loss information, the resultant, overall impulse response can be calculated. The impulse response shown in figure 6 combines the channel characteristics for the blue pair shown in figure 5 with the characteristic of the transmit and receive filters assumed in the CICTR[1] simulations. The transmit and receive filters used in this simulation are square-root raised cosine filters with a 0.08 roll-off factor at a symbol rate of 833 million symbols per second.

As can be seen from figure 6, which shows the insertion-loss impulse response as a function of symbol time, there is severe delay spread across many symbols which will result in a distortion known as inter-symbol interference (ISI). The adaptive equalization in the receiver must compensate for the ISI in order to ensure reliable 10GBASE-T performance.

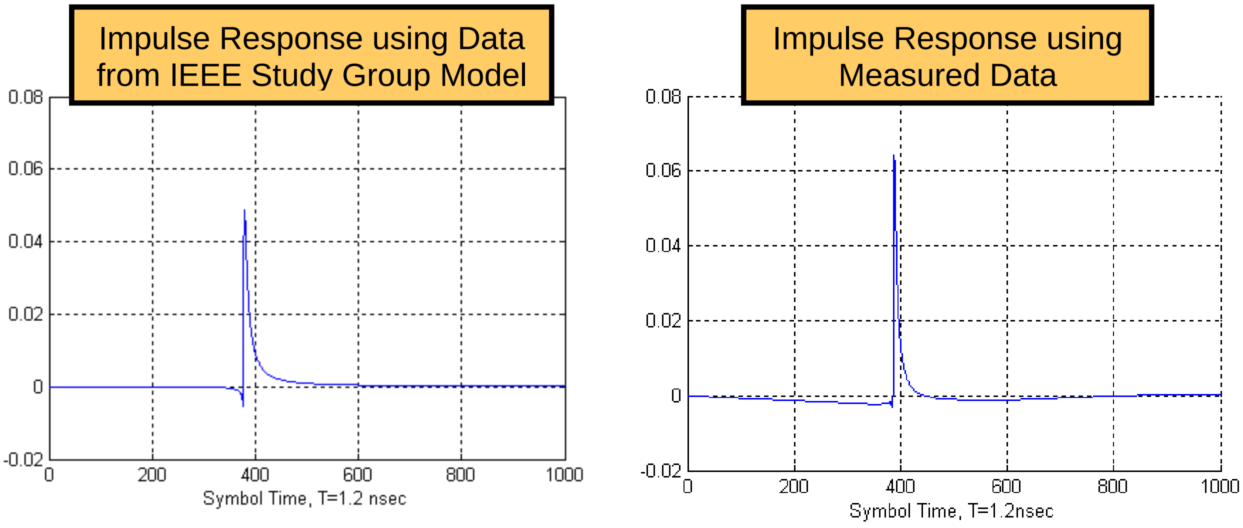

Figure 6: Combined Impulse Response of Channel and Filters

You will also note that there is a visible difference between the impulse response calculated using a smooth model and the impulse response calculated using measured data. These differences have potentially significant impact on the design of the adaptive equalizers that compensate for the resultant ISI distortion.

Using the CICTR simulation tools, the DFE performance is simulated using the impulse responses derived from using the category 6 model and from using measured data. The feedback and feed-forward designs were adjusted so that the DFE outputs of the two simulations were approximately the same as can be seen in figure 7.

Surprisingly, the two designs are drastically different. Using the category 6 model, 100 feedback and 120 feed forward taps were used in the DFE. However, when using the category 6 measured data, 450 feedback and 1200 feed forward taps were necessary to approximate the output of the model simulation.

The impact that cabling performance has on the design of modern LAN applications is clearly illustrated in this example. The DFE complexity is affected by almost an order of magnitude depending on the insertion loss information used in the simulation. Although scaling the data to a limit line may seem like a worst-case scenario, it can lead to incorrect conclusions. In this case, the phase non-linearity and insertion loss deviation (ILD) at high frequencies created a challenge for the digital signal processor used for the adaptive equalization.

Modern LAN cables must be designed and manufactured to offer stable, linear performance over a wide frequency range and ambient environmental conditions (temperature, humidity, etc.). This should include frequencies up to at least 500 MHz and ideally to 650 MHz or higher.

Reduced insertion loss is generally preferable since it will maximize the signal, resulting in improved signal to noise and reduced power requirements. However, simply looking at insertion loss margin may not tell the whole story. The impulse response performance offers a new and better way to interpret cabling performance to predict how the channel will perform when connected to actual network equipment.

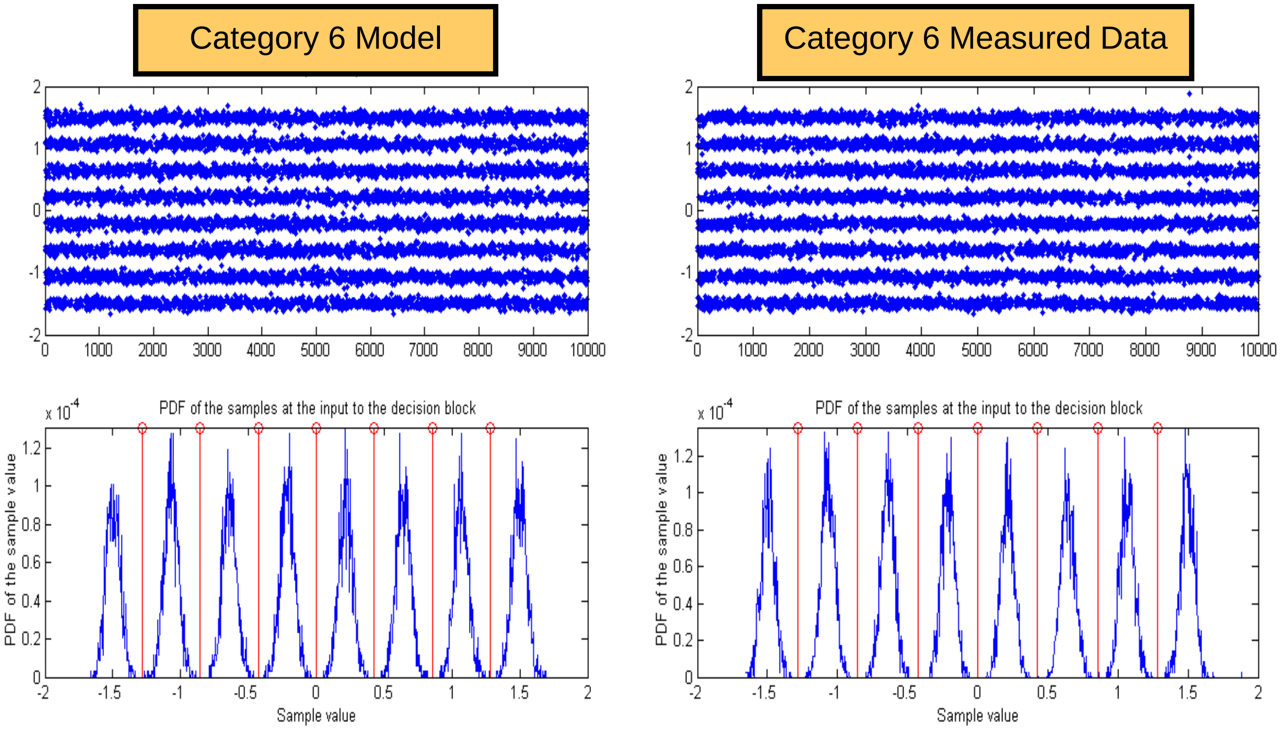

Figure 7: DFE Output using Modeled and Measured Category 6 Data

Alien Crosstalk

Alien crosstalk is a dominant noise source that limits the received signal-to-noise ratio (SNR) of a 10GBASE-T transmission system. Alien Crosstalk is extremely difficult to cancel using digital signal processing techniques. Even if used, DSP cancellation of alien crosstalk would add significant cost and complexity to the transceiver. Beyond the economic ramifications of the added complexity, questions arise regarding the ability to dissipate the additional heat within the transceiver and how to handle the added power consumption. As a result, requirements for alien crosstalk in cabling specifications are hastily being developed, but it remains poorly characterized and is installation dependent.

There are several methods that are available to mitigate alien crosstalk in a category 6 cabling system:

- Shielding: Employ a foil laminate tape beneath the jacket of the cable. These category 6 cables are known as FTP cables for foil-shielded twisted-pairs. No longer a UTP (unshielded twisted-pair) cable, FTP cables, when properly constructed, have very low alien crosstalk and greatly simplify the problem of operating 10GBASE-T over copper cabling.

- Spacing: By employing clever cabling geometries and physical spacers, it is possible to develop UTP category 6 cables that have improved alien crosstalk performance by pushing potential disturbing cables away from it.

- Balance: By improving the balance of the cable pairs, the alien crosstalk performance of the resultant cable can be improved. This is especially true for pair combinations that have harmonically related pair twist rates that are in close proximity.

Alien Crosstalk Measurement Issues

Alien crosstalk issues are further complicated since the industry has not reached consensus on how to measure and quantify this noise.

Most experts agree that the worst-case cable configuration is six disturbing cables bundled snugly around one, victim cable. However, you must be careful when evaluating alien crosstalk claims from cabling vendors. They may be measuring alien crosstalk with fewer disturbed cables or with the cables spaced farther apart (such as in a conduit). Although these alternative interpretations may be appropriate for certain niche cases, they are inadequate to ensure robust operation in common installation situations such as when using J hooks or cable trays. The worst-case test configuration, as seen in figure 8, approximates a cable tray or J hook installation environment.

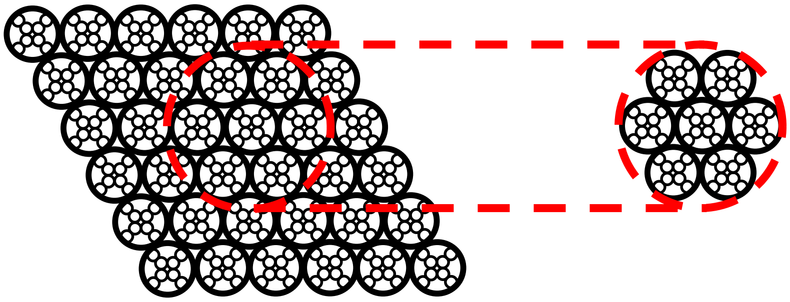

Figure 8: Test configuration approximates tray environment

The effect of the test configuration on the resultant power sum alien near-end crosstalk (PSANEXT) can be quite significant. An example is give in Figure 9, below, showing the PSANEXT of one pair tested in the worst-case cable configuration of six disturbing cables bundled snugly around one, victim cable. Also shown in the results of the same pair tested in a best-case configuration of two cables in a ½" metallic conduit. The conduit test method does not approximate the multi-disturber configurations common in today's cabling infrastructures.

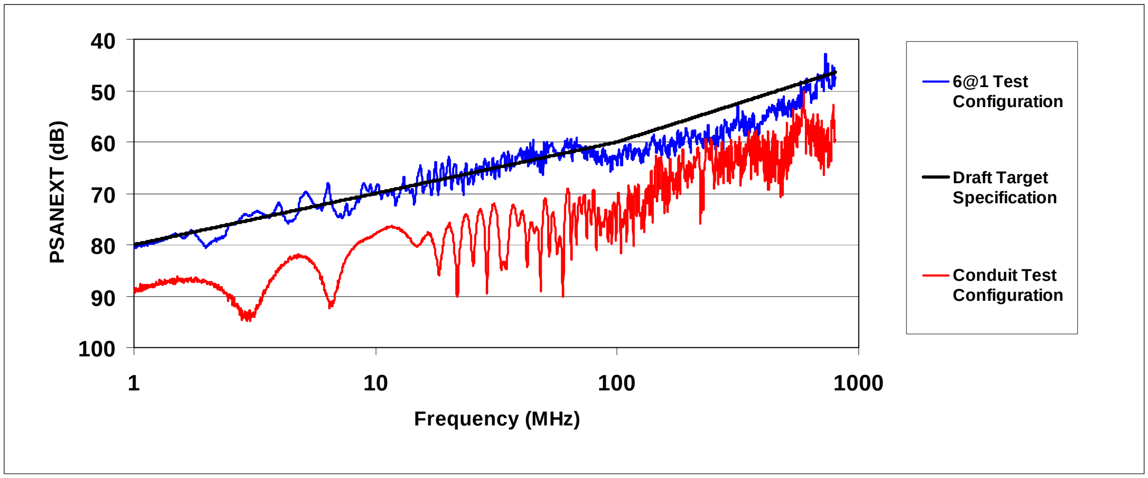

Figure 9: PSANEXT Differences due to Test Configuration

Most discussion regarding alien crosstalk is limited to alien near-end crosstalk. Crosstalk from alien, far-end transmitters can be very significant especially if the disturbing cables are much shorter than the victim cable, effectively amplifying the noise. PSAFEXT issues for UTP cabling have not been adequately explored by the industry and target performance levels have not been established.

The alien crosstalk performance as a function of length is not fully understood. You must be careful when evaluating an alien crosstalk guarantee to make sure that it includes all cables and components as well as the resultant channel and that the channel guarantee applies to all channel lengths including very short channels and 100-meter, four-connector channels as well as all combinations of channel lengths (e.g. short disturber channel with a long victim channel – critical for alien FEXT)

Cabling Balance

Twisted-pair cabling uses differential transmission as a means to reduce radiated emissions and susceptibility to noise. The two insulated conductors of a twisted pair are balanced with respect to ground meaning that they each have the same impedance between conductor and ground. This is very different from an unbalanced transmission line, such as coaxial cable, where the two conductors are not balanced with respect to ground and, therefore, have different impedance between each conductor and ground. In fact, the outer conductor in a coaxial transmission system is often tied to ground.

Differential transmission involves splitting the signal to be transmitted in half and transmitting one-half of the signal on one insulated conductor of the twisted pair and the other half of the signal, phase shifted by 180°, on the other insulated conductor of the twisted pair. The 180° phase shift inverts the signal to its opposite. In other words a "+1 volt" signal becomes a "–1 volt signal". The differential receiver, at the far end of the cable channel, subtracts the two signals, hence the term differential, so the original signal is restored.

The advantage of differential transmission is that any external noise, which couples onto the pair, will be cancelled at the receiver (by being subtracted out) as long as the noise signal is the same on both insulated conductors of the pair. Ideally, all unwanted noise and crosstalk is coupled equally onto both conductors of a pair and subtracted from the signal by the differential receiver. At the same time, any signal that radiates from one insulated conductor of the pair will add to the signal that radiated from the opposite insulated conductor of the pair canceling each other since they are opposite in polarity. This assumes that each insulated conductor is similar enough to the other insulated conductor for proper cancellation.

Pairs are twisted to improve immunity to noise and crosstalk as well as reduce emissions. In the real world, pairs are not perfectly balanced. Actual physical and electrical differences between the pairs cause unbalances that limit the amount of noise that will actually be the same on each insulated conductor or of signal egress that will be effectively cancelled. The finite balance of the pair can play a significant role in the ability of the system to meet radiated emission and noise susceptibility requirements. If the receiver cannot remove all the noise due to unbalances induced by the cabling it can lead to possible errors and poor network reliability. Cabling balance also plays an important role in controlling internal and alien crosstalk and other performance parameters. Poorly balanced pairs can also help transmit any unwanted common-mode signal coming from the transmitter due to limitations in its output signal balance (OSB).

Poorly balanced cable, due to differences in attenuation, time delay and impedance between the two insulated conductors of a twisted pair, can cause the differential signals propagating on the cable to distort. This will result in unwanted common mode signal and a distortion of the original differential signal. Since the receiver has a finite common-mode rejection ratio (CMRR), it will not be able to subtract the entire unwanted common mode signal from the twisted pair. Additionally, the distortion of the differential mode signal will be detected by the receiver causing the signal-to-noise ratio to degrade leading to an increased probability of error and possible reliability problems.

Well-balanced pairs are necessary to ensure proper operation of the transmitters and receivers and to control EMI of the complete system. In addition, they make sure that there will not be unexpected behavior in crosstalk or attenuation since the limits placed on these parameters assume balanced transmission. Even if screened or shielded cables are used, the shielding effectiveness should be thought of as an additional isolation method, above and beyond the cancellation effect of balanced pairs, and not as a substitute. If the cable has poor balance, common-mode signal can transfer from the cable to the electronics and radiate due to finite CMRR and OSB of the transceiver. To properly perform as a system, LAN cabling must be well balanced regardless of the presence of shielding.

Testing Balance

The question remains, how to ensure that cabling products are adequately balanced. Although under review, category 6 cable standards do not have adequate specifications for balance. Also, since balance, by definition, is a measure of the difference between each conductor and ground, another problem arises with UTP cable regarding the effective ground. Common-mode signals must have a return path also known as the ground path. In an unshielded cable the effective ground will be different depending on where and how the cable is installed. Thus, the ground will be different when the cable is installed in a metallic conduit as when it is installed in a plastic conduit. The resultant balance of the cable for each case will also be different. In a cable or cabling component specification, the problem is readily solved by defining the ground plane by either placing the cable in water or by suspending the cable away from ground. This is sufficient to give system developers a start, but they will need to also carefully consider changes due to different installation practices.

We are able to measure how well the pairs are balanced. Two methods will be described in this paper, which are referenced in various industry standards. The first is longitudinal conversion loss (LCL), which is sometimes called longitudinal balance. LCL is measured by applying a common-mode signal to the cable and measuring the resultant differential signal at the same cable end. The differential signal is caused by mode conversion within the cable due to imperfections in its balance. This method is somewhat similar to an impedance measurement since the same end of the same pair is used to both inject the test signal and to measure the result. Due to symmetry, LCL is the same as TCL (transverse conversion loss) although the test procedure is slightly different. LCL is also preferable to TCL as a test method due to its robustness to external noise.

The second measurement of pair balance is longitudinal conversion transfer loss (LCTL). Longitudinal Conversion Transfer Loss is similar to LCL in that a common-mode signal is applied to the cable pair and the resultant differential signal is measured. The difference is that in the LCTL measurement, the differential signal is measured at the opposite end of the cable in which the common-mode signal was applied. Also due to symmetry, LCTL is the same as TCTL (transverse conversion transfer loss) although the test procedure is also somewhat different.

Correlating Balance to Alien Noise and Crosstalk

Improvements to the pair balance will result in more robust operation for today's network application such as 1000BASE-T and will be a critical component for 10GBASE-T and other emerging applications.

In the following example, various commercially available UTP cables are installed as two-connector channels in a plastic raceway and are exposed to electrical fast transients (EFT) noise at increasing voltages. The network performance (frame errors) while running 1000BASE-T in full duplex is measured and subsequently correlated to cabling performance. Several samples of seven different brands of category 5e and category 6 cabling were tested. This testing duplicates difficult environments such as:

- Proximity to electrical motors and air conditioning units
- Elevators
- Factory environment

As can be seen in figure 10, there is a strong correlation between the immunity to EFT noise and the cabling balance. In this example, the correlation to longitudinal balance (LCL) is shown, but a similar correlation to ELTCTL also exists.

You will also note that in this particular cross-section of the cabling industry (seven cable brands), that there is an obvious segregation or difference between the balance of category 5e and category 6 cabling solutions and the resultant noise immunity.

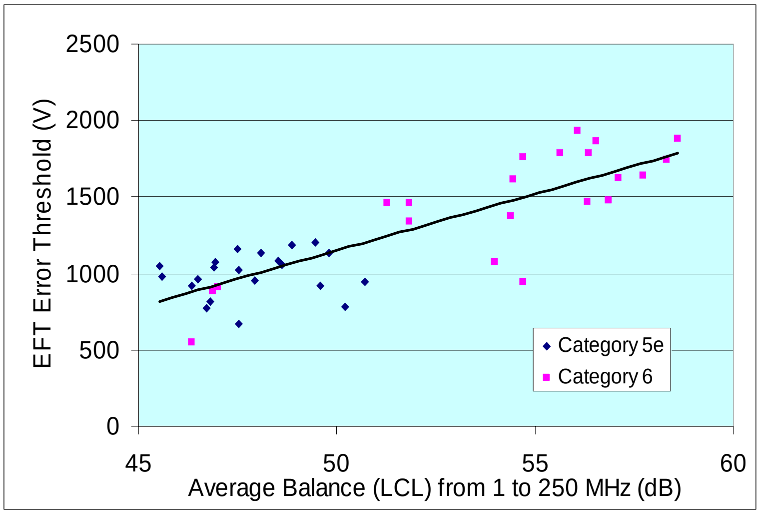

Figure 10: Noise Immunity correlating to Cabling Balance

Naturally, the question arises regarding correlation of the immunity of cabling to alien crosstalk noise and cabling balance. Although much work remains on this subject, it should be noted that although there is a direct correlation between cabling balance and alien crosstalk noise, there are other significant variables as well such as distance between the disturbing and victim pairs and harmonic relationship between the twist rates of the disturbing and victim pairs.

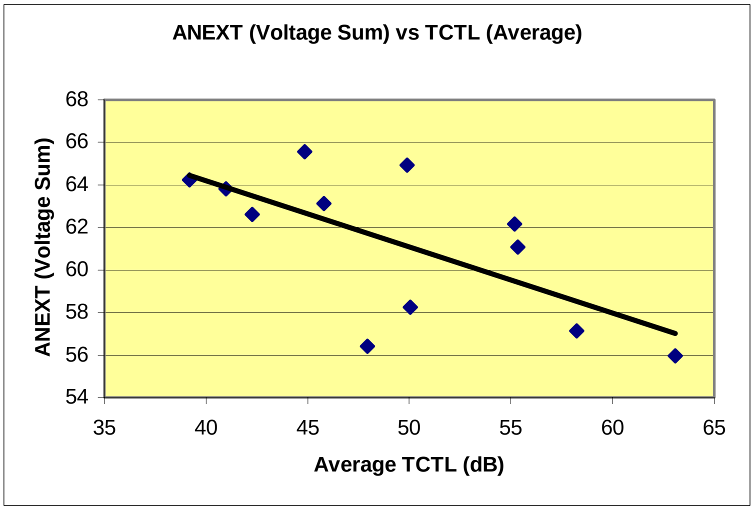

Figure 11: Alien Crosstalk related to Cabling Balance

Figure 11 shows the alien crosstalk performance of a commercially available category 6 cable, assembled into a worst-case bundle, as it relates to the balance of the cabling pairs. In this example, the Alien near-end crosstalk is depicted as a voltage sum where lower numbers are better.

Conclusions

Modern communication systems are no longer dominated by near-end crosstalk. Therefore, attenuation-to-crosstalk ratio (ACR) is no longer an accurate or applicable method to gauge signal-to-noise or predict how cabling will perform while running modern network applications. To accurately characterize signal-to-noise, all dominant noise sources at the receiver output must be considered. Communication systems are comprised of active and passive devices. The signal and noise are affected by all components of the system including interactions. For example, crosstalk noise created in the passive cabling system will be reduced both by the attenuation of the cabling system and the DSP cancellation in the receiver.

Bit error rate is an important metric of network reliability and ensuring adequate signal-to-noise under real-world conditions. Real-world conditions will affect signal-to-noise and the resultant bit error rate. It is important to have reliable network operations with the conditions under which the network will be actually operating.

Channel capacity can tell us the growth potential of our communication channel to support higher data rates, but must be used with caution. Users need to be careful when comparing channel capacities of two different channels to make sure an apples-to-apples comparison is being accomplished. Pay attention to differences in assumptions than can have a significant and even drastic effect on channel capacity.

In certain cases, such as alien crosstalk, the industry has not achieved consensus on measurement method or configuration. This can further confuse capacity claims since drastic differences could exist solely because the alien crosstalk assumptions are based on two different measurement configurations (conduit vs. cable tray, for example.)

Modern Cabling Systems must be designed and manufactured with features to ensure robust network performance of the latest LAN applications such as today's 1000BASE-T and tomorrow's 10GBASE-T. This includes:

- Stable, linear performance over a wide range of ambient conditions (temperature, humidity, etc.) at frequencies up to at least 500 MHz and ideally to 650 MHz or higher.

- Better Insertion Loss (attenuation) is key for improving signal-to-noise and reducing power consumption.

- Improvements in balance (such as LCL and ELTCTL) will improve the immunity of cabling to external noise including alien crosstalk. It is also an excellent metric for the quality and consistency of the manufacturing process for modern LAN cables and cabling components.

- Since the IEEE P802.3an project was just started in March 2004, consider a shielded cabling solution if you need to maximize the compatibility with the eventual 10GBASE-T standard. The reality of the situation is that the Alien Crosstalk performance levels for existing UTP cables are not known.

The cabling industry has a proven track record of innovation. In time, alien crosstalk and other issues will become clear and UTP solutions will emerge to support this application with specifications, recommendation and procedures developed to ensure robust application support.

References

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