Alien Crosstalk: The Limiting Noise Factor in Category 6A Channel Performance

Introduction

Today's Category 6A (CAT 6A) systems are impacted by an increasing amount of noise. The typical environment for a data center is characterized by multiple Ethernet protocols running over a significant volume of different cable designs, performance levels, and manufacturers' brands. All of these elements provide a very noisy environment for 10GBASE-T systems.

It is generally understood by most in the Ethernet industry that active equipment is able to eliminate much of the internally generated noise within a 10GBASE-T channel. However, many in the industry are not aware that cancellation technology has improved, making alien crosstalk (AXT) the limiting factor in the overall noise level of 10GBASE-T systems.

This white paper explains that the overall noise level for CAT 6A channels can only be improved by adding additional immunity to AXT in the system.

The 10GBASE-T Channel

The Ethernet protocol for 10Gb/s over twisted pair cabling, IEEE 802.3an 10GBASE-T, uses a standard CAT 6A cabling channel. CAT 6A cabling performance requirements are defined in TIA-568-C.2. CAT 6A component requirements are set for constructing reference implementation channels, up to 100m length with 4 connectors, thus providing a minimum performance necessary to support 10GBASE-T data link operating at maximum 10^{-12} bit error rate (BER).

The ideal cabling channel has no loss and no noise, because the two transceivers at the ends of a link are connected directly to each other. By introducing cabling component losses into the channel from intervening cable and connectors, the signal level is lowered and the noise level is raised, thus reducing the signal-to-noise ratio (SNR) as well as the system capacity.

Why 10GBASE-T is More Sensitive to Noise

10GBASE-T uses five times the bandwidth of 1000BASE-T. For example, 10GBASE-T operates at frequencies five times higher than 1000BASE-T where a good SNR is more challenging to achieve. 10GBASE-T also uses much more of the available CAT 6A channel capacity over its channel bandwidth than 1000BASE-T uses over its CAT 5e channel bandwidth. 10GBASE-T transmits signals at a much faster rate, and with much more complexity than 1000BASE-T.

In the typical CAT 6A application, there is a significant volume of cables bundled together where each cable will transmit a portion of its signal onto adjacent cables. This coupling of transmitted signal onto adjacent cables is known as alien crosstalk (AXT), and it is a key contributor to the overall noise level in a CAT 6A channel. The noise sensitivity of 10GBASE-T is the reason that AXT is a factor in overall data transmission performance.

Cabling Performance Parameters

There are six (6) key electrical characteristics that are defined by industry cabling standards and which define the allowable levels of noise in a channel. Together, these 6 parameters as defined by ANSI TIA-568-C.2, are used to calculate the Signal to Noise Ratio (SNR) for a CAT 6A cabling system.

TIA-568-C.2, CAT 6A channel parameters; SNR factors
INSERTION LOSS (IL)
RETURN LOSS (RL)
POWER SUM NEAR-END CROSSTALK (PSNEXT)
POWER SUM ATTENUATION TO CROSSTALK RATIO FAR-END (PSACRF)
POWER SUM ALIEN NEAR END CROSSTALK (PSANEXT)
POWER SUM ATTENUATION TO ALIEN CROSSTALK RATIO FAR-END (PSAACRF)

Signal Level

Signal loss is the decrease in magnitude or the power loss of a signal that propagates between points, and it is usually determined by the resistance, size, and length of the conductors. Dielectric losses, or the loss of power or energy, also affect the signal levels. Together, signal and dielectric losses determine attenuation (insertion loss).

The power sum of the cascaded channel components' attenuations and reflections determine the insertion loss (IL) of the channel. The total channel IL, with respect to frequency, determines the signal response for the channel.

Noise Levels

Total channel noise is determined by the sum of all of the major noise parameters: RL, PSNEXT, PSACRF, PSANEXT, and PSAACRF.

- Signal reflection loss is limited by the total channel return loss (RL) specifications. Although it is a transmission parameter, RL is treated as noise and is included as a contributor to the noise sum.
- Internal Crosstalk: PSNEXT and PSACRF are the primary sources of internal channel noise (i.e. channel self-crosstalk between 4 pairs carrying the 4 parts of the 10Gb/s data link).
- Alien Crosstalk: PSANEXT and PSAACRF are the primary sources of external channel noise (i.e. external crosstalk from nearby channels carrying different data links' signals that interfere with a particular channel).
- Noise Floor: The "inherent noise," or often called "external in-band and out-of-band noise," is sometimes referred to by the Ethernet alliance as "externally-induced background noise".

Figure 1 depicts the maximum levels of signal loss and noise loss across the 500 MHz of usable spectrum for a 100 meter length (the maximum allowed distance) CAT 6A channel.
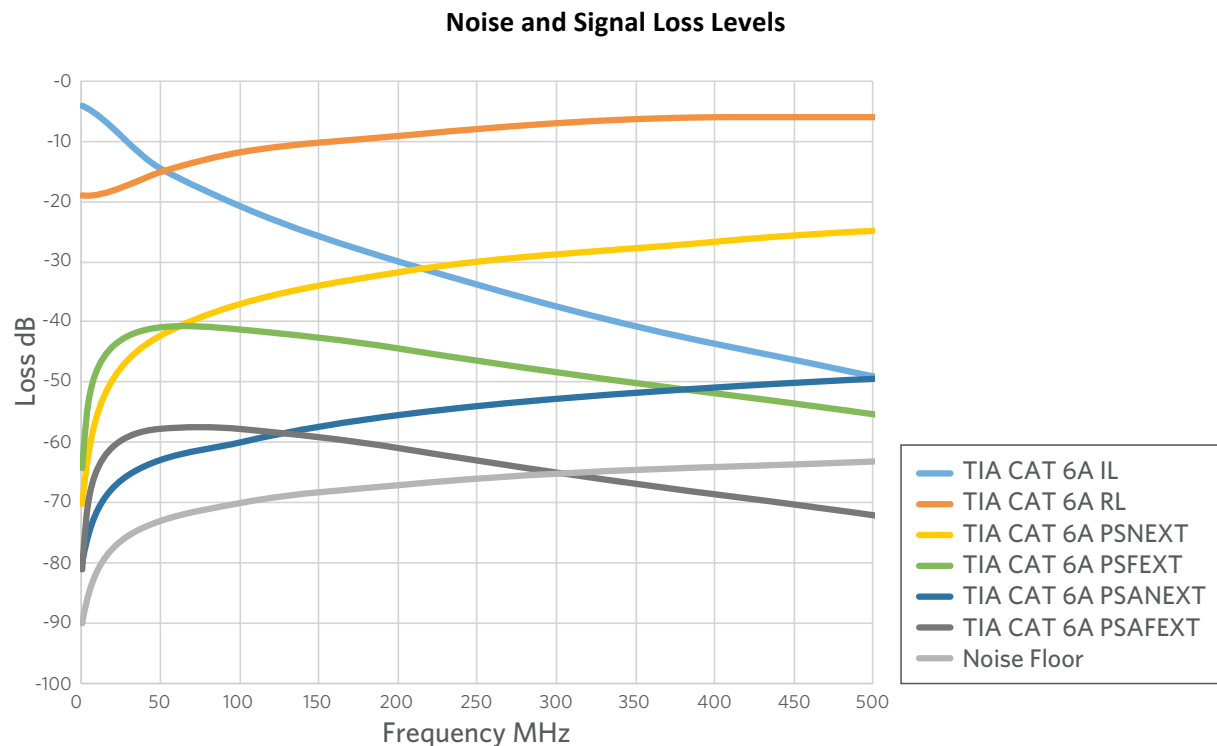

Figure 1 **Channel Parameters, TIA limits**

The total noise within a channel is the power sum of all internal crosstalk, alien crosstalk, return loss, plus the addition of external sources of in-band and out-of-band noise.

$$SNR\ (dB) = S\ (dB) - N\ (dB)$$

$$SNR\ (dB) = IL\ (dB) - (PS\ (PSNEXT,\ PSFEXT,\ PSANEXT,\ PSAFEXT,\ RL))\ (dB)$$

The signal (IL) and power sum noise total (PSN1) for all TIA-568-C.2 limits are shown in Figure 2. It is important to point out that PSN1 represents the total *maximum* noise level allowed for the CAT 6A cabling system BEFORE any active component NEXT or FEXT cancellation techniques are employed. Note: RL is "cancelled" in the above calculation to reveal the total crosstalk noise.
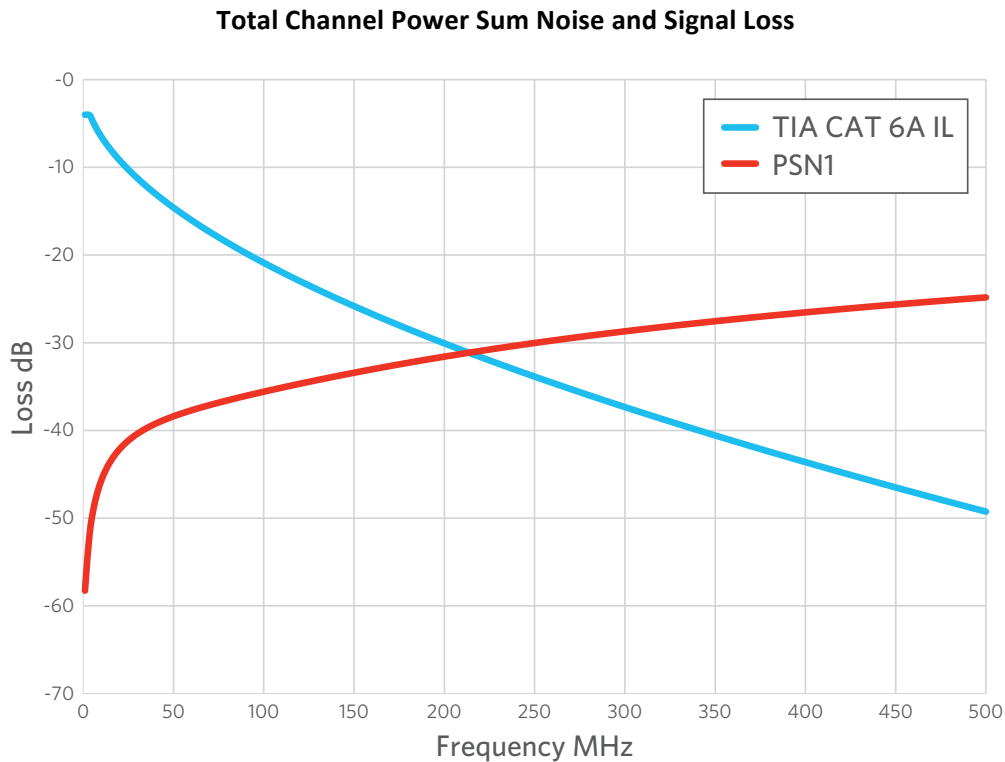
Total Channel Power Sum Noise and Signal Loss

Figure 2 **TIA CAT 6A IL and Power Sum Losses**

The SNR falls below zero just above 200 MHz. 10GBASE-T would not be able to operate at these levels of SNR without other means of reducing the noise levels in the channel. There are two (2) fundamental ways of improving the SNR of the channel to acceptable levels:

1) Utilizing cable components that prevent noise from exceeding TIA limits and/or reduce attenuation of the desired signal.
2) Using active components to eliminate noise that exists in the channel.

Cabling Component Design Improvements

Transmission and crosstalk parameters performance levels may be improved so that they significantly exceed TIA-568C.2 performance standards, but improvements come at a price. Insertion loss improvements are constrained by allowable cable diameter. Return loss is controlled by minimizing component impedance mismatch, which is limited by controlling individual component RL. Internal cross talk can be improved through tighter twist at the cost of attenuation or through further separation of conductors at the cost of cable diameter. The possibility for significant Alien crosstalk reduction is afforded by the introduction of an overall cable shield, but it is very difficult to achieve alien crosstalk margin in a UTP cable.

Signal Processing Improvements

Transmission and crosstalk parameters performance levels may also be improved by analog and digital signal processing within the transceiver. 10GBASE-T transceivers operate at a rate of 2.5 Gbps

on each copper pair, with a maximum of 10^{-12} BER. To achieve the BER, multiple technologies are used in order to reduce or remove noise.

The 10GBASE-T includes additional technologies beyond the basic ones used for 1000BASE-T. As the data rates increased with Ethernet progression, copper PHY has become increasingly more sophisticated to operate over UTP cabling. Figure 3 shows the progression of PHY technology used to achieve the higher data rates. [1]
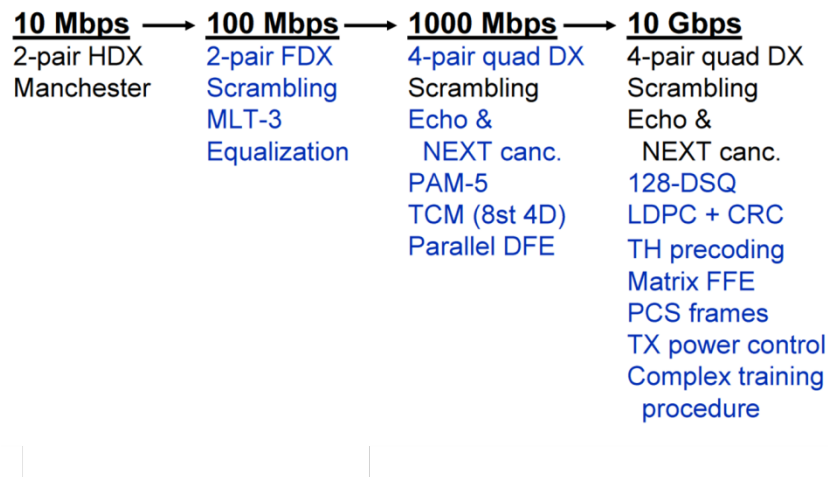
10 Mbps	100 Mbps	1000 Mbps	10 Gbps
2-pair HDX	2-pair FDX	4-pair quad DX	4-pair quad DX
Manchester	Scrambling	Scrambling	Scrambling
	MLT-3	Echo &	Echo &
	Equalization	NEXT canc.	NEXT canc.
		PAM-5	128-DSQ
		TCM (8st 4D)	LDPC + CRC
		Parallel DFE	TH precoding
			Matrix FFE
			PCS frames
			TX power control
			Complex training
			procedure

Figure 3 **Progression of Copper PHY Technology**

There are several techniques deployed in 10GBASE-T systems to reduce noise in the system. These include coding algorithms, cancellation techniques, digital signal processing (DSP) and radio frequency interference (RFI) cancellation.

- Coding algorithms help reduce errors in TX/RX:

  - Tomlinson Harashima (TH) Pre-coding allows better performance of the receiver as the transceiver pre-compensates the impairments of the system.

  - Low Density Parity Check (LDPC) Error Correction Coding (encoding on transceiver and decoding on receiver) offers performance close to the limit of the channel according to Shannon's capacity law.

- Cancellation techniques:

  - Echo cancellation is used mainly to reduce RL. Echo cancellation levels > 55 dB can be realized[2]

  - Intersymbol interference (ISI) is a form of distortion between signals in time, and it is the primary source of bit errors, primarily due to dispersion (higher frequencies being more susceptible to losses than lower frequencies). Multi-rate filter banks are used for crosstalk cancellation. Equalizers/DSPs provide internal noise cancellation.

- DSP provides significant filtering and compensation benefits. Forward error correction (FEC) effectively improves SNR through "coding gain." This DSP technique is done at the expense of latency. Signals from adjacent pairs (NEXT) are individually cancelled using the equalizers of each pair's transceivers. The same technique is used for FEXT. <u>Cancellation of PSNEXT > 40 dB and PSFEXT >20 dB can be realized.</u>[2]

- RFI cancellation (cell phones/walkie-talkies)

  - Analog and digital cancellations are combined and used in order to reduce the noise more efficiently. They mitigate by using RS codes and longer interleaver.

An illustration of the noise cancellation effect can be found in Figure 4[3].

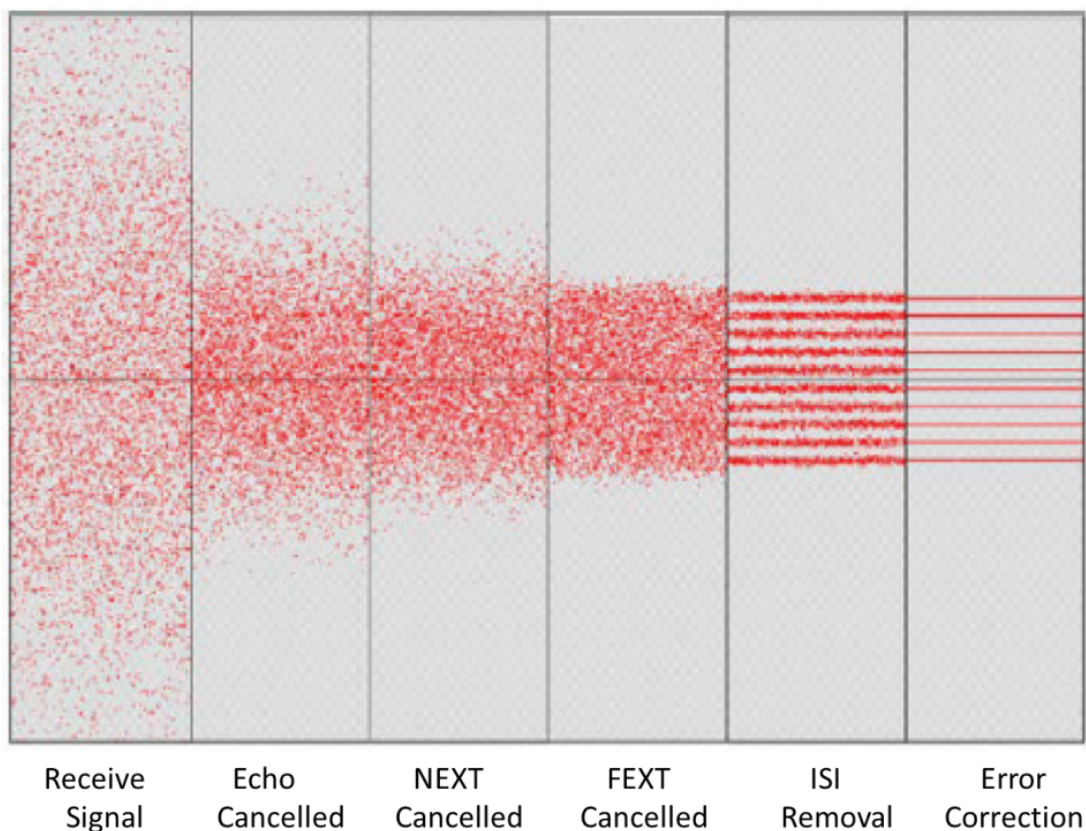| Receive Signal | Echo Cancelled | NEXT Cancelled | FEXT Cancelled | ISI Removal | Error Correction |

Figure 4: **Illustration of Impact of Cancellation Techniques**

As shown earlier in Figure 2, noise levels in the CAT 6A channel would be unacceptably high without additional noise mitigation techniques.

Today's 10GBASE-T active components (PHY) employ cancellation technologies (>55 dB RL; >40 dB NEXT; >20 dB FEXT) that are sufficient to effectively push internal RL/NEXT/FEXT well below the allowed AXT noise level. Figure 5 depicts the effect that noise cancellation technologies have on internal PSNEXT levels in comparison to the AXT TIA limit.
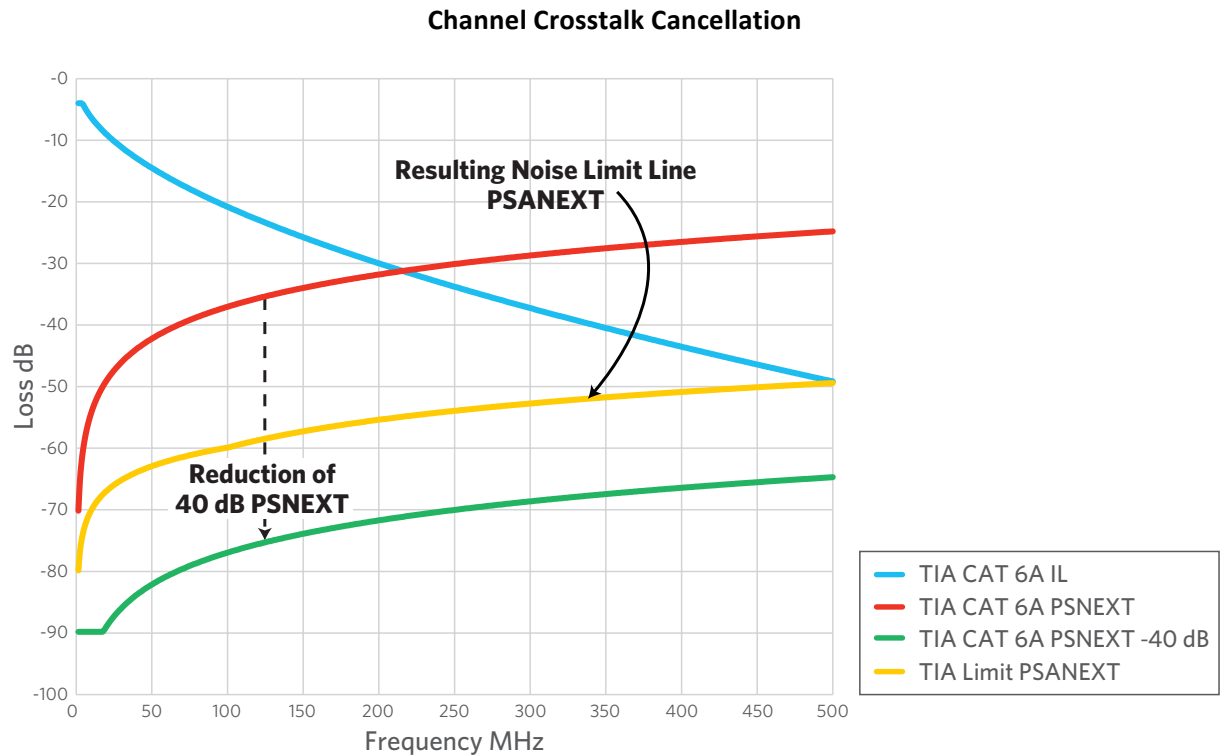
Channel Crosstalk Cancellation

Figure 5 **Channel Crosstalk Cancellations**

In Figure 5, the left arrow shows the effect of having 40 dB of PSNEXT noise cancellation in the channel. As a result of this internal noise cancellation, the noise contribution from PSNEXT is more than 10 dB below the noise contribution in the channel from AXT. At the 40 dB NEXT cancellation level (typical of today's PHY technology), internal NEXT becomes an insignificant contributor to total noise in the channel.

How to Improve Your Channel Performance

Figure 6 shows the total power sum of the noise allowed (PSN1) by the TIA standard versus the worst case signal level (IL). PSN2 represents the total power sum noise level in the channel AFTER noise cancellation has been employed (55 dB for RL, 40 dB for PSNEXT, 20 dB for PSFEXT). The dashed line, PSN3, represents the total noise level with an additional 4 dB of noise cancellation for PSNEXT and PSFEXT. That is, the dashed line, PSN3, represents the total noise level with 44 dB of PSNEXT cancellation and 24 dB of PSFEXT cancellation.
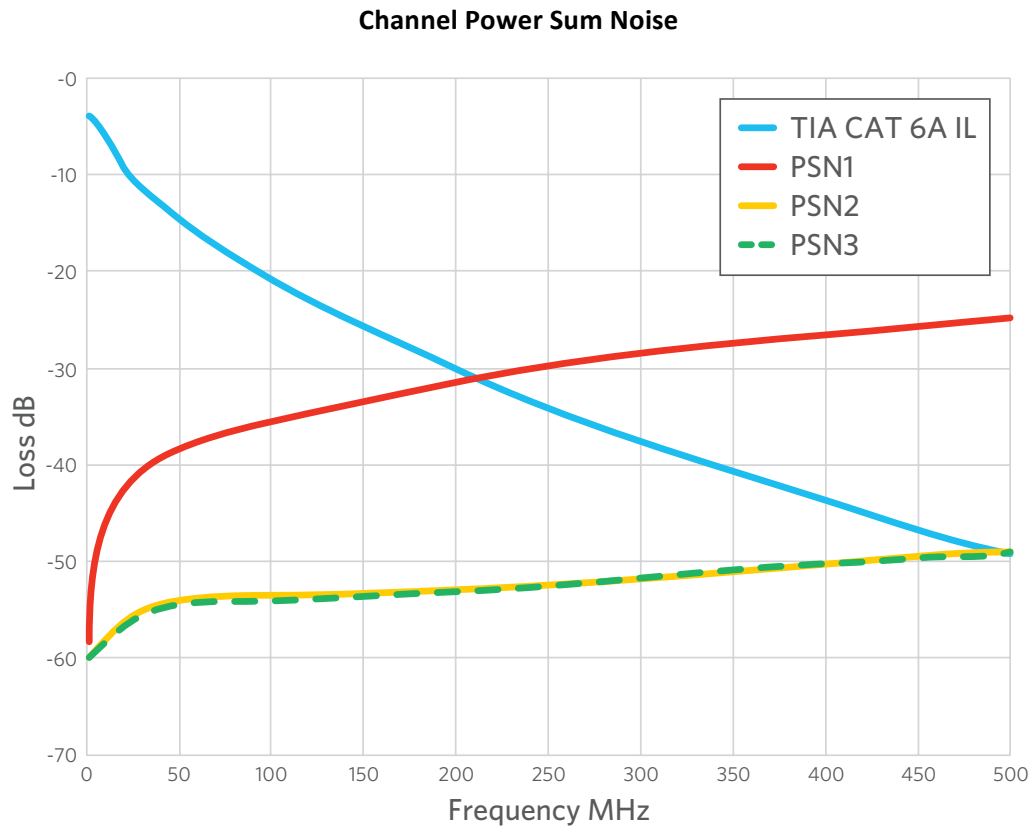
Channel Power Sum Noise

Figure 6 **Effect of Adding Additional NEXT on Overall Power Sum Noise**

The additional +4dB of PSNEXT and PSFEXT cancellation does not provide further lowering of the total power sum noise level. That is, the lines PSN2 and PSN3 are nearly identical.

Figure 7 takes this analysis a step further and shows the impact on the total noise level by adding 6 dB of additional AXT margin to the cabling system. Because AXT is the limiting noise factor in the channel, the specific improvement to alien crosstalk margin translates directly into a lower total noise level. In other words, reducing AXT levels by 6 dB has the effect of lowering the total power sum noise level by 6 dB.
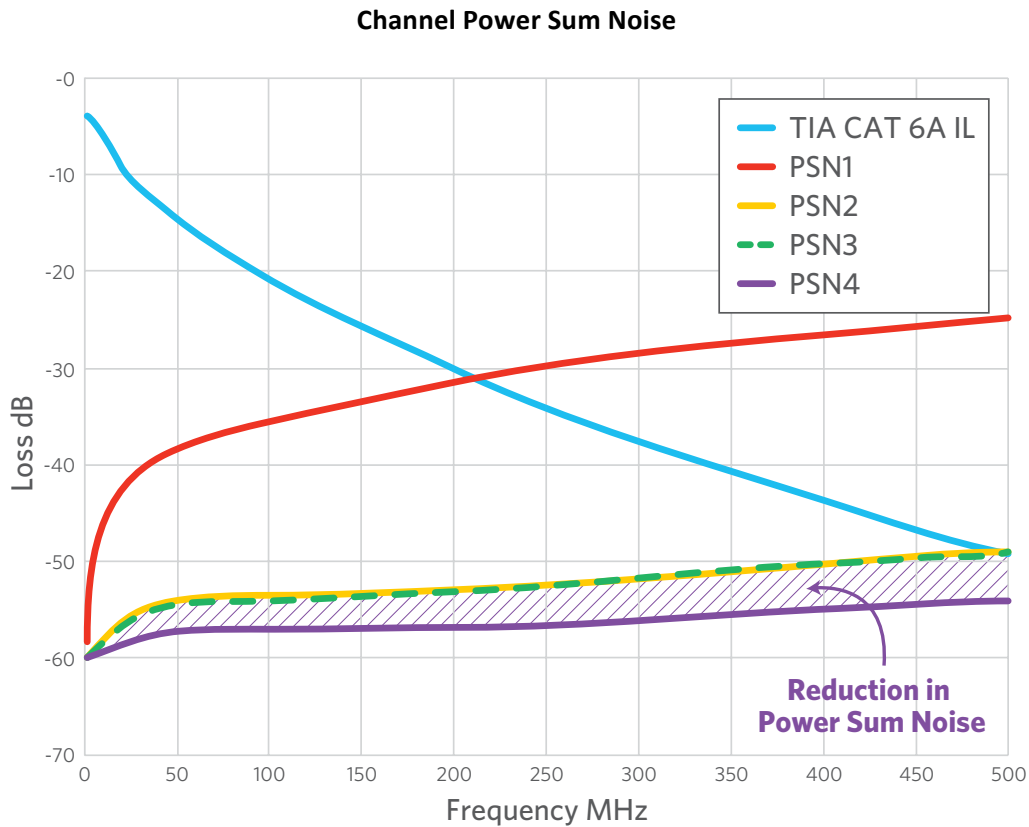
Channel Power Sum Noise

Figure 7 **Channel Power Sum Noise, Enhanced CAT 6A Channel**

Why is Alien Crosstalk Margin Important for 10BASE-T?

In a perfect world, all CAT 6A cables and connectivity are perfectly balanced. In reality, there are asymmetries between tip and ring conductors, which cause capacitance and inductance between each conductor and a virtual ground to be different (unbalance). This unbalance can increase crosstalk coupling between adjacent cables beyond the levels that the cables are specified for. Additionally, unbalances within connecting hardware can generate noise that is transmitted down the disturber cable to create additional differential noise in victim cables. In the TIA-568-C.2 requirement for AXT, CAT 6A designs are tested in a 6-around-1 design using identical cables. In actual installations, different Category cables, such as CAT 5e or CAT 6, are often installed adjacent to these CAT 6A cables. The impact of these adjacent cables can be significant if the CAT 6A cable is not sufficiently immune to AXT. All of these factors can introduce additional alien noise that the typical CAT 6A cabling system is not necessarily designed to protect against.

- CAT 6A cables and connectors are never perfectly balanced

    - Asymmetries between tip and ring cause capacitance and inductance between each element and virtual ground to differ

    - Additional unbalance between tip and ring can increase the amount of alien crosstalk coupling between cables

    - Unbalance in connecting hardware can generate noise, which is radiated down the disturbing cable

- Typical CAT 6A UTP cables are designed specifically to reject AXT from adjacent cables of the same design (i.e., other identical CAT 6A cables)

    - When disturber cables are CAT 6 cables or from other manufacturers, AXT performance may suffer

CAT 6A Cable Surrounded by Six CAT 6 Cables

As detailed in this paper, AXT is the limitation noise factor for CAT 6A channels. In the data center application space, cable-to-cable coupling (alien crosstalk has been identified as the primary source of signal interference) is increased by the normal use of large bundles of cables. Cable-to-cable coupling is greater at higher frequencies. It is not simply proportional to frequency as other forms of signal interference (e.g. basic common-mode noise). Moreover, the possibility for significant coupling is greater because of the common mixing of cables with various performance categories and various original manufacturers.

To illustrate this effect, we performed an AXT test by using one CAT 6A cable (victim cable) surrounded by six CAT 6 cables (disturber cables). As can be seen on left chart in Figure 7, an industry standards compliant CAT 6A UTP cable fails the PSANEXT requirement by 7 dB. This cable is not designed to protect against AXT from CAT 6 or CAT 5e cables. The right chart of Figure 7 shows the results of this same test using Superior Essex 10Gain® XP Cat 6A UTP cable. It is specifically designed to suppress all forms of AXT, and it passes this test with +4 dB margin. This 11 dB difference in AXT performance between 10Gain XP and the standard compliant CAT 6A cable translates into 11 dB of additional total noise margin for the channel using 10Gain XP.
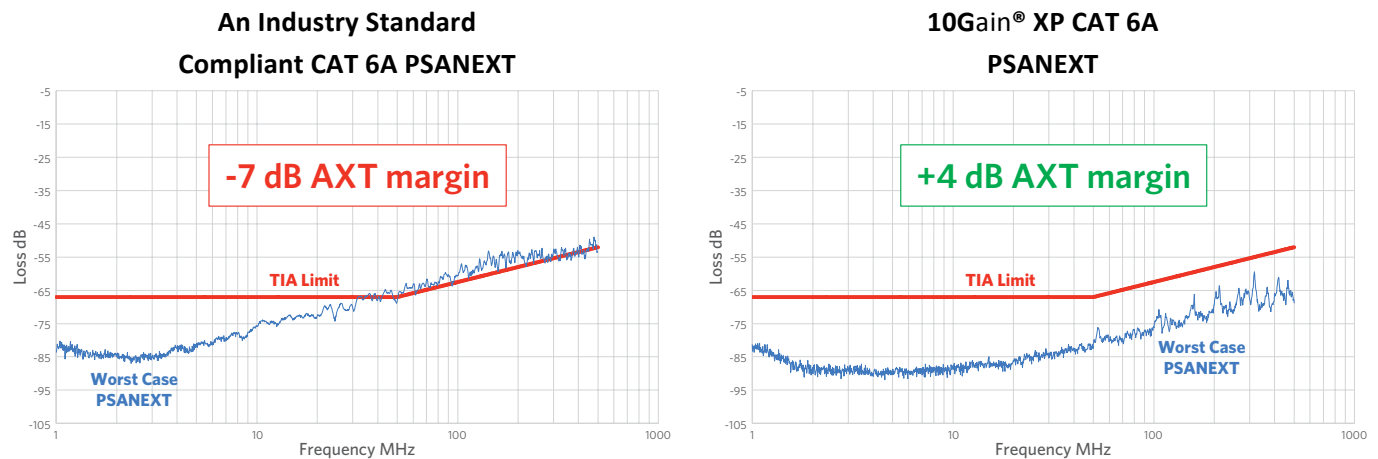
Figure 8 **Comparison of Cable Performance without and with Alien Crosstalk Margin**[4]

Summary

Noise cancellation technologies employed by PHY chips used in today's 10GBASE-T transceivers have improved greatly since 2006 when 10GBASE-T was first ratified. The consequence of these technical advancements is that the effective noise level in the channel from internal crosstalk (PSNEXT, PSFEXT) is now much lower than the noise levels caused by AXT. Although all types of noise sources are mitigated by 10GBASE-T coding technologies, true noise cancellation is not effective on alien crosstalk-induced noise.

As a result of these active component noise cancellation techniques, AXT is now the limiting noise factor in CAT 6A channels. In order to lower the total noise level in a CAT 6A channel, reduction in AXT noise is necessary. Today's 10GBASE-T transceivers are not able to cancel noise received from adjacent cables. Consequently, the most effective way to add margin to the channel performance is to choose a cabling system that provides guaranteed AXT margin above the TIA-568-C.2 minimum requirements.

The corollary to this finding is that CAT 6A cabling systems that provide guaranteed margin for NEXT, PSNEXT, FEXT, PSFEXT, and RL are not providing the system with any additional true benefit in terms of lowering the total noise level in a CAT 6A channel.

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[2]ClassEA and ClassFA cabling for 10GBASE-T and 40GBASE-T, 2011, R1M, www.rdm.com

[3]10GBASE-T: 10 Gigabit Ethernet over Twisted-pair Copper, Version 1.0 August 2007, Ethernet Alliance, www.ethernetalliance.org

[4]Superior Essex Product Development Center Internal Test Reports #TR5282 and #TR5182, November 2013.

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