Alien Crosstalk Response of Augmented Category 6 Balanced Cables due to the Proximity Effect

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***Abstract*—The objective of this paper is to discuss the response of Cat.6A balanced cables used as transmission media for high-speed data communications in structured cabling systems. An analysis of alien crosstalk based upon the proximity effect is made as well as a comparison between the responses of UTP (Unshielded Twisted Pair) and F/UTP (Foil/Unshielded Twisted Pair) cables in presence of alien crosstalk is presented. Alien crosstalk mitigation techniques in telecommunications cabling systems are discussed as well.**

I. INTRODUCTION

In order to support transmissions at 10Gb/s, especially the 10GBASE-T (IEEE 802.3an) application over balanced cabling systems (or telecommunications cabling systems), the Telecommunications Industry Association (TIA) with support of IEEE developed a new cabling category – the Augmented Category 6 (Cat.6A), whose bandwidth is 500MHz. This is the bandwidth requirement of the application 10GBASE-T (10Gigabit Ethernet, 10GbE) running on balanced cabling systems in a 100-meter channel in commercial buildings.

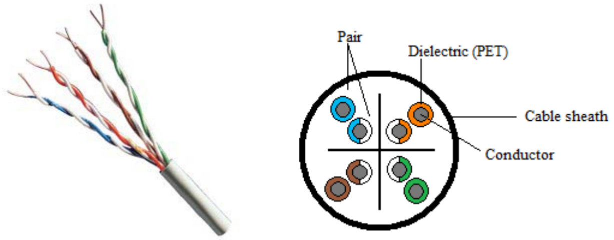
Balanced or twisted pair cables have been used as transmission media for digital communications in LANs (Local Area Network) inside commercial buildings since the middle of the 1980's. Although transmission performance of balanced cables are well known, their use for very high-speed communications represents a new challenge in terms of their responses for a special kind of crosstalk - the alien crosstalk.

Crosstalk interference is the major transmission impairment of unshielded twisted pair (UTP) cables for high-speed data communications. For this reason, special attention to techniques and measures to mitigate this interference has been paid by cables and cabling systems' manufacturers.

Structured cabling are generic cabling systems built with a common transmission media, which is able to support a variety of telecommunications services in commercial buildings such as voice, image and data, among other low-voltage applications. The standardized transmission media for this purpose is the 100-ohm, 4-pair, twisted pair cable. Although unshielded and screened cables are recognized as transmission media for structured cabling, most of the buildings are cabled with UTP cables.

It is also important to mention that optical cables are recognized as transmission media for structured cabling systems implementation, but almost 100% of the telecommunications outlets are terminated with balanced copper cables.

Figure 1 depicts a typical 4-pair UTP cable employed in structured cabling systems in commercial buildings. Figure 1a shows a four-pair UTP cable sample and Figure 1b presents the pairs configuration inside cable sheath.



(a) (b)

Fig. 1. a) Unshielded Twisted Pair cable sample, b) Pairs configuration inside the 4-pair cable's sheath

One can see in Figure 1b a central "cross" element. This is present in most of the Category 6 UTP cables available in the market place. This simple element is an effective technique to keep a safe distance between pairs inside the cable sheath thus decreasing internal crosstalk between the four pairs in a given UTP cable.

However, in real life installations, cables are placed in bundles on raceways and cable trays, in conduits, in the racks and cabinets as well as other pathways in commercial buildings. Although crosstalk interferences between pairs inside the same cable are well known and controlled, some interference between pairs of different UTP cables in a given cable bundle is expected and out of control. This is referred to as alien crosstalk. Figure 2 shows this effect.

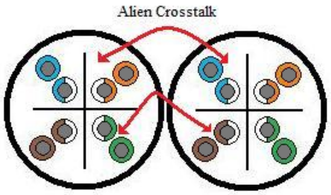


Fig. 2. Representation of alien crosstalk interference between two UTP cables placed in the same bundle

Thus, the proximity between UTP cables in a cable bundle is critical for alien crosstalk coupling; closer the pairs of different cables; higher the alien crosstalk interference. Keeping safe separations between the conductors is not only a good approach to minimize crosstalk, but necessary to assure proper transmission performance for high-speed data transmission as 10GBASE-T over balanced cables in structured cabling systems.

Hence, the focus of this study is on alien crosstalk response analysis based on the proximity effect for unbalanced Category 6A UTP cables.

II. SKIN EFFECT AND PROXIMITY EFFECT MODELING

As a result of an alternating current flowing through a given conductor of a cable, its magnetic field will induce currents in the near conductor in the same or an adjacent cable. These induced currents oppose the flow of the primary conductor's current then causing the currents to concentrate on the surface of the conductor as frequency increases.

At very high frequencies the current is confined almost entirely to a thin skin near the surface of the conductor. This is referred to as skin effect.

The skin effect in solid cylindrical conductors depends on the "x" parameter, which can be determined as follows

$$\mathrm{x} = 2\,\pi\,\mathrm{r}\sqrt{\frac{2\mu\,\mathrm{f}}{\sigma}} \qquad (1)$$

Where,

μ is the material permeability;

f is the operation frequency;

σ is the material resistivity;

r is the conductor radius.

For copper cables, 23AWG gauge, at the range of temperature usually found in commercial buildings (20ºC degrees, typically), σ value is 1721 mho/m, so the "x" parameter can be written as follows [4]

$$\mathrm{x}_{\mathrm{copper}} = 0.2142\,\mathrm{r}\sqrt{\mathrm{f}} \qquad (2)$$

The skin effect is responsible for increasing the conductor resistance as the frequency increases. It's also responsible for decreasing the inductance as the frequency increases.

One can relate the "x" parameter with resistance values at d.c. and at high frequencies as well according to the following expression [6]

$$\frac{\mathrm{R}}{\mathrm{R}_0} \cong \frac{\mathrm{x}}{2\sqrt{2}} \qquad (3)$$

Where,

R is the resistance at high frequency (a.c. resistance);

R_0 is the d.c. resistance;

x is the skin effect parameter.

The internal inductance of the conductor can be derived from the following expression [6]

$$\frac{X}{R_0} = \frac{\varpi L_0}{R_0} = \frac{\sqrt{2x}}{4} - \frac{3\sqrt{2}}{32x} \qquad (4)$$

ω equals to 2πf;

X is the conductor reactance;

x is the skin effect parameter.

The d.c. resistance of a matched pair of conductors is twice the d.c. resistance of each conductor. However, due to the proximity effect this is not true for the a.c. resistance. This effect decreases the current density in the conductors which are closest together. Figure 3 depicts the configuration of the pairs subject to the proximity effect [6].

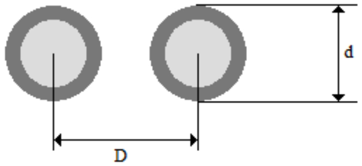


Fig. 3. Pairs configuration for proximity effect analysis

The proximity effect is proportional to the ratio of the conductor's diameter (d) and the separation between them (D) in a cable or cable bundle. A good approximation for the proximity effect of an isolated pair can be obtained by the following expressions [6]

$$\frac{R}{R_0} = \frac{1}{4}\left(1 + \sqrt[6]{3^6\,\frac{8\cdot x^6}{(1-d/D)^2}}\right) \qquad (5)$$

$$\frac{X}{R_0} = \frac{\varpi L_0}{R_0} = \frac{0.455\cdot x^6}{\left(1+\sqrt[6]{3^6}+8\cdot x^6\right)\sqrt{1-(d/D)^2}} \qquad (6)$$

With all the parameters used in these formulas already described in previous expressions in this article.

III. CHANNEL MODEL AND PRIMARY LINE PARAMETERS

Transmission lines or channels can be represented by distributed network parameters such as resistance, inductance, capacitance, and conductance per unit length. The network parameters (R, L, G and C) are assumed to be uniformly distributed over the channel length. In practice a differential model is adopted [5].

Copper cable channels can be approached as a cascade of symmetrical T sections mathematically represented by a two-port transmission matrix whose analytical parameters are classical and well-known or by a set of differential equations obtained by assuming a differential length of line, calculating the voltage and the current at the input and output of the cable section for Δl approaching zero. Classical results obtained from this analysis can be seen below.

$$V_l = C_1 e^{\gamma l} + C_2 e^{-\gamma l} \qquad (7)$$

$$I_l = C_1 Y_0 e^{\gamma l} - C_2 Y_0 e^{-\gamma l} \qquad (8)$$

Where V_l and I_l are the voltage and the current along the transmission line respectively. C_1 and C_2 are determined by boundary conditions at the source and line's termination. Y_0 is the characteristic admittance and γ is the propagation constant of the channel related as follows

$$Y_0 = \sqrt{\frac{Z}{Y}} \tag{9}$$

$$\gamma = \sqrt{Z\mathrm{Y}} = \alpha + j\beta \tag{10}$$

Where α is the attenuation constant and β is the phase constant, with

$$Z = R + j\omega L \tag{11}$$

$$Y = G + j\omega C \tag{12}$$

A. Resistance

The d.c. resistance (R_0) of a copper conductor is an important parameter as it limits the magnitude of the electrical current that will flow through the conductor. However, due to the skin effect, the higher the frequency the higher the conductor resistance for a fixed length. This resistance is referred to as a.c. resistance (R).

B. Inductance

The inductance is almost independent of the frequency of operation. However, it tends to decrease as frequency increases due to the skin effect.

The general forms of the mutual inductance are presented in the expressions below

$$L = \frac{\mu_0}{n\pi} W + L_0 \quad \text{H/m} \tag{13}$$

$$L = k_L \cdot W + L_0 \quad \text{H/m} \tag{14}$$

Where,

k_L = 0.4 for balanced conductors;

L_0 is the internal inductance.

The constant W is a dimensionless geometric factor depending on the physical arrangement of the conductors. In a good arrangement (e.g.: an UTP cable), W is the same for both mutual capacitance and mutual inductance. For different conductors' configurations, where the electric and magnetic fields do not have the same boundaries, W is approximately the same for the capacitance and the inductance.

For a balance unshielded pair of conductors, W can be calculated as follows

$$W = \cosh^{-1}(D/d) = \ln\left\{(D/d)\left[1 + \sqrt{1-(d/D)^2}\,\right]\right\} \tag{15}$$

Thus,

$$L = 0.4\cosh^{-1}(D/d) + L_0 \tag{16}$$

$$L = 0.4\ln\left\{D/d(1 + \sqrt{1-(d/D)^2}\,]\right\} + L_0 \quad \text{H/m} \tag{17}$$

For D/d>3, equation ( ) reduces to

$$L = 0.4\ln(2D/d) + L_0 \quad \mu\text{H/m} \tag{18}$$

In this study, the value of the internal inductance (L_0) is obtained by means of the following expression

$$|Z_0| = \sqrt{\frac{L_0}{C_N}} \tag{19}$$

Where,

$|Z_0|$ is the characteristic impedance (Ω);

L_0 is the internal inductance (μH);

C_N is the nominal capacitance of the cable (nF/m).

This approach is very simple while efficient and accurate as proven in prior studies as presented in [4].

C. Capacitance

Mutual capacitance tends to attenuate high frequency signals transmitted over copper cables. The capacitance is also a determining factor of crosstalk response for copper cable. Mutual capacitance can be expressed as follows

$$C = \frac{n\pi \cdot \varepsilon_0 \varepsilon_R}{W} \quad \text{F/m} \tag{20}$$

And

$$C = \frac{\varepsilon_R}{k_C \cdot W} \quad \text{nF/m} \tag{21}$$

Where,

k_C = 36 for balanced conductors;

W is the same as shown in equation (15).

For a balanced pair of conductors, the mutual capacitance can be calculated according the expression below

$$C = \frac{\varepsilon_R}{36 \cdot \cosh^{-1}(D/d)} \tag{22}$$

$$= \frac{\varepsilon_R}{36 \cdot \ln\left\{(D/d)(1 + \sqrt{1-(d/D)^2}\,]\right\}} \quad \text{nF/m} \tag{23}$$

For D/d>3, equation (23) reduces to

$$C = \frac{\varepsilon_R}{36 \cdot \ln(2D/d)} \quad \text{nF/m} \tag{24}$$

Where ε_R is the permittivity of polyethylene, which value is 2.25 for a wide frequency range [7].

Figure 4 shows the behavior of ε_R as function of frequency. As one can see in the chart, this parameter is constant for a wide frequency range.

1) Capacitance unbalance

Capacitance unbalance (ΔC) is a significant effect to be taken into account when modeling copper cables. It is responsible for increasing the mutual capacitance of these cables. Capacitance unbalance pair-to-pair can be expressed as follows

$$\Delta\mathrm{C}_{\mathrm{PP}(l\,)} = 181 \cdot l \ \text{(nF)} \tag{25}$$

Where l is the conductor’s length, in meters (m).

Thus, in this study, the general form of the mutual capacitance including the proximity effect as well as the capacitance unbalance is expressed as follows

$$C = \frac{\varepsilon_R}{36 \cdot \ln\left\{[(D/d)(1+\sqrt{1-(d/D)^2}]\right\}} + \Delta C_{PP} =$$

$$= \frac{\varepsilon_R}{36 \cdot \ln\left\{[(D/d)(1+\sqrt{1-(d/D)^2}]\right\}} + 181 \cdot l \ \text{(nF)} \qquad (26)$$

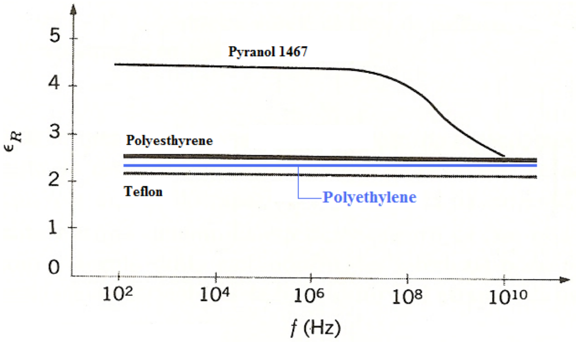


Fig. 4 Polyethylene permittivity as function of frequency

D. Conductance

For polyethylene-insulated cables, the conductance (also referred to as mutual conductance) is extremely low, and can be neglected in the channel model without any loss of accuracy. In other words, the conductance does not affect the secondary parameters of a cable: impedance, propagation delay, phase shift as well as attenuation.

IV. CROSSTALK MODELING

In this study crosstalk coupling mechanisms (near end crosstalk and far end crosstalk) were modeled according to the classical Campbell’s formula [2]. This formula was initially developed for the analysis of electrically short parallel conductors’ elements with equal lengths and terminated by loads with equal characteristic impedances. The scheme depicted in Figure 5 can be used for deducing the Campbell’s formula.

The voltage source V_1 creates a current $2i_c$ through the pair-to-pair mutual capacitance C and a current i_c flows to both ends of the circuit 2 (disturbed pair). Current I_1 is responsible for inducing a voltage in the disturbed pair due to the mutual inductance L and a loop current i_l flows through circuit 2 (notice the direction of i_l in both ends), that can be expressed as

$$i_l = \frac{v_N}{2Z_0} \qquad (27)$$

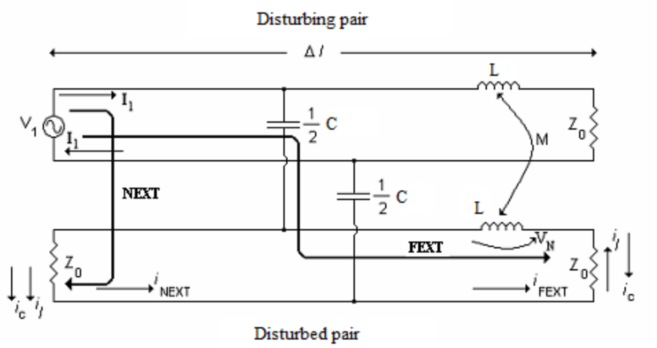


Fig. 5 Crosstalk coupling mechanisms (NEXT and FEXT)

V_N, which is the noise voltage induced in the disturbed pair due to I_1 (in the disturbing pair) can be defined as follows

$$V_N = j\omega L \, I_1 \qquad (28)$$

Thus the crosstalk current due to the inductive coupling can be re-written as

$$i_l = j\frac{\omega L \, I_1}{2Z_0} \qquad (29)$$

By measuring the induced signal at the near-end, one can notice that the polarity of the inductive and capacitive couplings are coincident. As a matter of fact, the phases of i_c and i_l can oppose to each other or not. This behavior shows that if the effects of the inductive coupling are added to the effects of the capacitive coupling for NEXT, they will be subtracted for FEXT or vice-versa. Thus crosstalk currents i_c and i_l tend to add in the near-end (taking the end where the noise source V_1 is placed as reference) and subtract in the far-end.

Then, Campbell’s formula can be written as

$$\frac{I_2}{I_1} = \left[\frac{j\omega C \, Z_0}{8} \pm \frac{j\omega L}{2Z_0}\right] \qquad (30)$$

Where,

$\omega = 2\pi f$

f is the operation frequency (Hz)

L is the mutual inductance (H)

Z_0 is the characteristic impedance (Ω).

Still in terms of relations between currents, crosstalk coupling can be written through the Campbell’s formula, in dB, as

$$Xtalk = 20\log\frac{I_2}{I_1} =$$

$$= 20\log\left(\frac{j\varpi C Z_0}{8} \pm \frac{j\varpi L}{2Z_0}\right) \ \text{dB} \qquad (31)$$

Thus, from the equation (30) we can express NEXT and FEXT couplings as follows

$$NEXT = 20\log\left(\frac{j\omega C\ Z_0}{8} + \frac{j\omega L}{2Z_0}\right)\text{dB} \qquad (32)$$

$$FEXT = 20\log\left(\frac{j\omega C\ Z_0}{8} - \frac{j\omega L}{2Z_0}\right)\text{ dB} \qquad (33)$$

V. CROSSTALK AND ALIEN CROSSTALK ANALYSIS METHODOLOGY AND RESULTS

Figure 6 depicts samples of Category 6A UTP cables and the placement of the pairs of conductors inside these cables. For this cable category the separation between any configuration of two closest pairs inside a given cable is approximately 2mm, and the separation between any configuration of two farthest pairs inside a given cable is approximately, 3.5mm. Then, the average separation between any two pairs inside a given cable is 2.75mm.

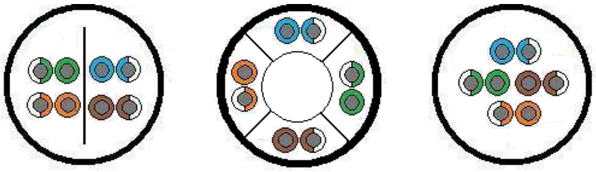


Fig. 6 Samples of pairs placement inside Cat.6A UTP cables

Considering the separations between pairs in Cat.6A cables and the diameter of its conductors, it's possible to determine the following ratios

$$\frac{D}{d} = \frac{2.75}{0.58} = 4.74, \text{ and } \frac{d}{D} = \frac{0.58}{2.75} = 0.21$$

Where 0.58mm is the diameter of the conductors of Cat.6A cables (23AWG). Analysis methodology consists in calculating the mutual capacitance and the mutual inductance of the conductors based on the ratios D/d and d/D as well. As D/d > 3, equations (18) and (24) can be used to calculate L(μH/m) and C(nF/m), respectively. In order to make the model more accurate, the pair-to-pair capacitance unbalance (ΔC_{PP}) can be determined using equation (25) and added to the value of C obtained through equation (24).

Once the values of L and C are determined, equations (32) and (33) can be used to calculate NEXT (dB) and FEXT (dB), respectively. Figure 7 shows NEXT and FEXT response for a combination of any two pairs of a UTP Cat.6A cable for a frequency range between 1MHz and 500MHz, whose length is 100m (this is the maximum channel length according to applicable structured cabling standards like the ISO/IEC 11801:2008 2nd edition – Amendment 1, ANSI/TIA-568-C Series, etc.).

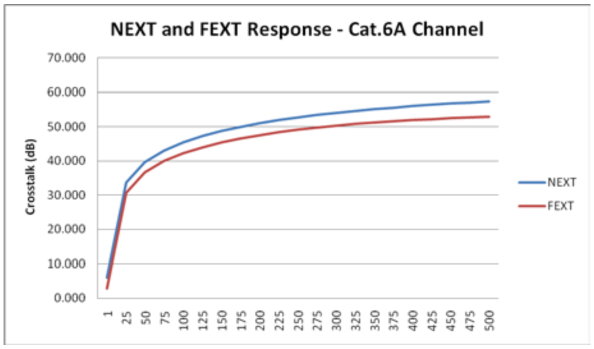


Fig. 7 Responses of NEXT and FEXT of a Cat.6A UTP cable

When arranged in bundles (as shown in Figure 2), the average separation between any configuration of two closest pairs between two Cat.6A UTP cables is approximately 3mm, and the separation between any configuration of two farthest pairs between two Cat.6A UTP cables is approximately, 8mm. Thus, the average separation between any two pairs of different cables within a bundle of Cat.6A UTP cables is 5mm.

According to applicable cabling standards (ISO, TIA, etc), alien crosstalk interference will affect pairs of adjacent cables in a 'six-around-one' bundle model as shown in Figure 8. Pairs of other cable segments out of the boundaries of this bundle will not be affected by alien crosstalk of any pair in the bundle.

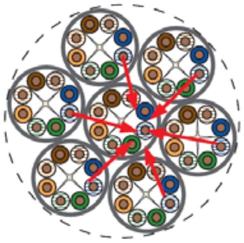


Fig. 8 Six-around-one bundle model for alien crosstalk evaluation

Then, considering the average separation between pairs of cables in a bundle of Cat.6A UTP cables as well as the cable diameter, the following ratios can be determined

$$\frac{D}{d} = \frac{5.0}{0.58} = 8.62, \text{ and } \frac{d}{D} = \frac{0.58}{5.00} = 0.11$$

Applying the same analysis methodology as for NEXT and FEXT interference, one can compute ANEXT (Alien Near End Crosstalk) and AFEXT (Alien Far End Crosstalk) for Cat.6A UTP cables. The responses of ANEXT and AFEXT of any two pairs within the cable bundle model shown in Figure 8 for a frequency range between 1MHz and 500MHz, whose length is 100m, can be observed in Figure 9.

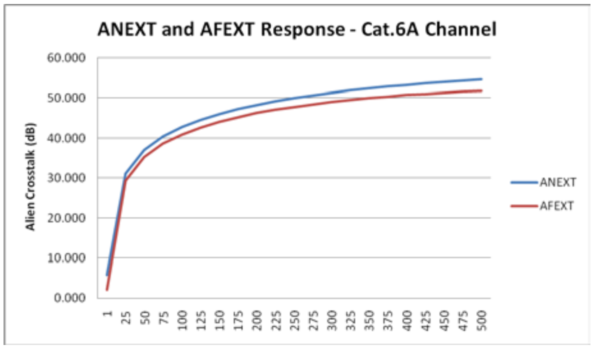


Fig. 9 Responses of ANEXT and AFEXT of a Cat.6A UTP cable

A better understanding of the difference between both responses, for crosstalk and alien crosstalk can be seen in Figure 10. The difference in responses for crosstalk and alien crosstalk is approximately 5dB, which is a very low difference for these parameters in practice.

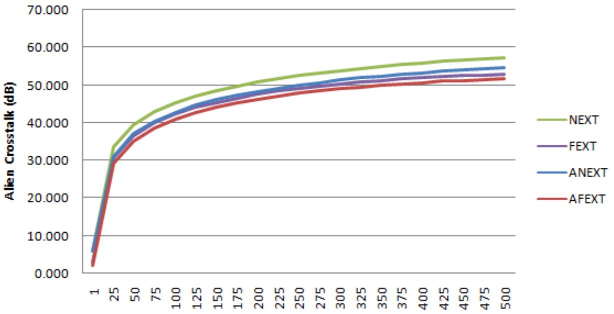


Fig. 10 Comparison between the responses of crosstalk and alien crosstalk as result of the application of the model presented in this study

VI. CONCLUSION

Cable manufacturers have developed specific cable construction techniques in order to mitigate alien crosstalk interference in bundles of Cat.6A UTP cables. The focus of these approaches is basically on providing additional separation between pairs of different cables placed in the same pathway infrastructure and that will be subject to alien crosstalk interference. Techniques to accomplish this additional separation include:

- the insertion of other cable elements to keep the pairs of the cable in its center and then far apart from pairs of adjacent cables within a bundle,
- the creation of spaces filled with air or polyethylene in the cable in order to keep its pairs in a fixed position and farthest of pairs of adjacent cables within a bundle,
- the use of a thicker layer of polyethylene in the cable sheath, thus providing some additional separation between pairs of adjacent cables placed within a bundle, among other similar approaches.

As a result of this, Cat.6A cables are expensive, heavier, and have bigger diameters thus requiring additional space in the cable pathway infrastructure, which contribute to increase the cost of implementation of structured cabling systems based on this cable category. In addition, cabling systems' manufacturers and standards recommend special installation practices in order to guarantee minimum category 6A performance in real life installations.

According to the methodology of crosstalk and alien crosstalk analysis and modeling described in this study, one can see that the responses of Category 6A unshielded twisted pair cables for crosstalk and alien crosstalk are very similar. In other words, Cat.6A UTP cables do not offer good protection against alien crosstalk in structured cabling systems. Also, considering that alien crosstalk is critical for 10GBASE-T performance assurance when using UTP cables, other types of transmission media should be considered.

Applicable cabling standards also recognize F/UTP (Foil/Unshielded Twisted Pair) cables for category 6A cabling systems implementation. These cables are basically the same UTP Cat.6A cable covered with an overall cable shield as shown in Figure 11.

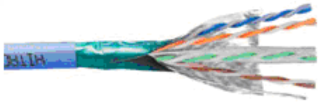


Fig. 11 Sample of a F/UTP cable recognized by applicable standards

The response of F/UTP cables for alien crosstalk is much better than UTP cable's response. As a matter of fact, F/UTP cables are immune to alien crosstalk interference. Figure 12 presents the comparison between UTP versus F/UTP cables for Category 6A in regards to the limit established by applicable standards (ANEXT response shown).

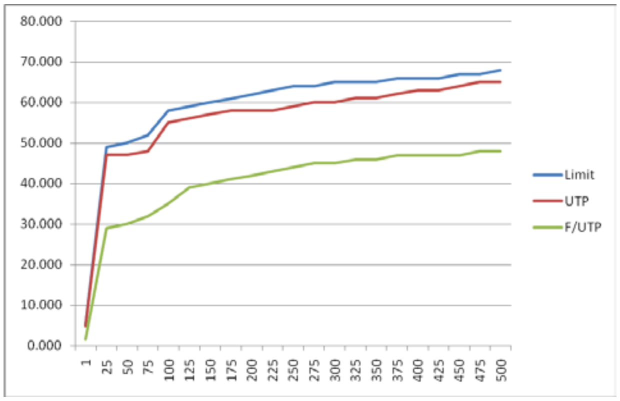


Fig. 12 Comparison between UTP and F/UTP Cat.6A cables for ANEXT

As shown in Figure 12, one can see that while UTP cables present a marginal response for alien crosstalk in the frequency range of interest, the use of F/UTP cables offer a much better insulation reaching approximately 20dB insulation between pairs for the alien crosstalk effect.

In addition to a much better alien crosstalk performance, Cat. 6A F/UTP cables are less expensive, lighter as well as have smaller diameters than some Cat.6A UTP cables available in the market place.

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