ANALYSIS OF PERFORMANCE DEGRADATION IN UTP CABLES AND ITS EFFECTS ON LAN APPLICATIONS

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***Abstract*- In this study, attenuation and crosstalk behaviours of unshielded twisted pair (UTP) cables are analyzed and according to the results of these analyses UTP installation in high-speed LAN applications are discussed. Also comments about the new, unstandardized UTP types and their applications in the area of data communication are given.**

I. INTRODUCTION

Unshielded twisted pair (UTP) copper cables represent an adequate transmission medium for a broad range of networking applications. A typical network installation consists of several subsystems. The two main subsystems are the backbone subsystem and the horizontal subsystem. The backbone subsystem provides the connection between wiring closets and the horizontal subsystem connects the telecommunication closets to desktops. In new installations, backbone wiring tends to be fibre. For the horizontal subsystem, UTP is still the wiring choice and is likely to remain so in the near future.

In the EIA/TIA classification of UTP cables for high-speed digital transmission [1], the properties of UTP Category 3 (UTP-3) cables correspond to those of voice-grade cables and the specifications for UTP Categories 4 and 5 (UTP-4 and UTP-5) cables define the properties of data-grade cables.

This paper discusses the data transport capability of UTP cables.

II. CHANNEL MODELİNG IN MULTIPLE PAIR CABLES

Parameters that determine the channel model of a multiple pair cable are line attenuation, crosstalk between adjacent pairs, reflection noise originated from impedance fluctuations of the cable and external impulse noises. In many cases, impedance fluctuations of Category 3, 4 and 5 cables can be neglected. Since reflection noises and external impulse noises are more than ten times smaller than crosstalk noises, they are not considered in this study.

In high frequencies, line attenuation can be formulated as

$$\begin{aligned}\alpha &= 0.5R\left(\sqrt{C/L}\right) + 0.5G\left(\sqrt{L/C}\right) \\ &= \left(R/2Z_0\right) + \left(GZ_0/2\right)\end{aligned} \tag{1}$$

where $Z_0 = \sqrt{L/C}$ is the line impedance, R is the resistance of the conductor, L is the inductance of the conductor, C is the capacitance between two conductors and G is the conductance between conductors in high frequencies.

Crosstalk is the signal generated by any pair of the cable on the adjacent pairs mainly because of the electromagnetic couplings between pairs. There are two types of crosstalk named near-end crosstalk (NEXT) and far-end crosstalk (FEXT) as shown in Fig. 1.

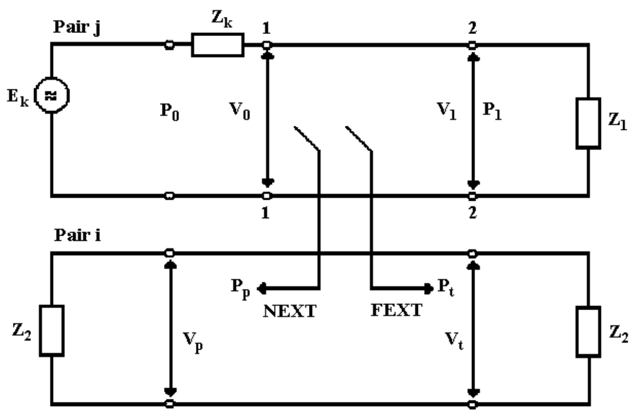

Fig. 1. Near-End and Far-End Crosstalk

NEXT can be expressed as the logarithm of the ratio of the power P_p received at the left end of pair i to the power P_0 transmitted from the same end of pair j.

$$A_n = -10\log\left|P_p / P_0\right| \quad [\mathrm{dB}] \tag{2}$$

FEXT can be expressed as the logarithm of the ratio of the power P_t received at the right end of pair i to the power P_0 transmitted from the left end of pair j.

$$A_f = -10\log\left|P_t / P_0\right| \quad [\mathrm{dB}] \tag{3}$$

A_n and A_f can be also written in terms of capacitive and inductive couplings between adjacent pairs as,

$$A_n = -20\log\left|(I_c - I_m)/I_0\right| \quad [\mathrm{dB}] \tag{4}$$

$$A_f = -20\log\left|I_c + I_m / I_0\right| \quad [\mathrm{dB}] \tag{5}$$

where I_0 is the current of pair j and I_c and I_m are the currents inducted by capacitive and magnetic couplings, respectively. Since

$$I_c = j\omega.\frac{I_0.Z_0.C_u}{8}, \; I_m = -j\omega.\frac{I_0.M}{2Z_0} \tag{6}$$

where Z_0 is the characteristic impedance of adjacent pairs with the assumption of Z_1=Z_2=Z_0, C_u and M are capacitive and inductive couplings, NEXT and FEXT can be formulated as

$$A_n = -20\log\left(\omega.\left|\frac{Z_0.C_u}{8} + \frac{M}{2Z_0}\right|\right) \quad [\mathrm{dB}] \tag{7}$$

$$A_f = -20\log\left(\omega.\left|\frac{Z_0.C_u}{8} - \frac{M}{2Z_0}\right|\right) \quad [\mathrm{dB}] \tag{8}$$

It can be clearly seen from the above formulae that I_c is bigger in pairs with high characteristic impedances and I_m is more effective in pairs with low characteristic impedances. Considering the fact that the impedance of a symmetrical line is high at low frequencies and decreases to a fixed value as the frequency increases, dominant factors for NEXT and FEXT are capacitive couplings at low frequencies and inductive couplings at high frequencies [2].

It is obvious that the channel model of a pair must include NEXT and FEXT effects to the transmission, as shown in Fig. 2, where $N_n(f)$ is the effect of near-end crosstalk and $N_f(f)$ is the effect of far-end crosstalk.

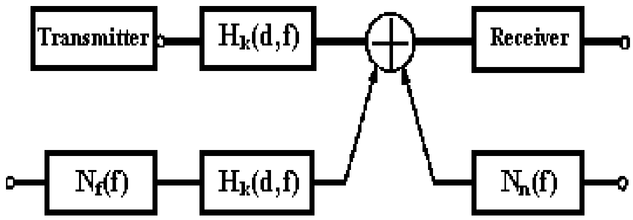

Fig. 2. Channel Model of A Pair

The transfer function $H_k(d,f)$ of the channel with length d can be written as follows

$$H_k(d,f) = e^{-d\gamma(f)} = e^{-d\alpha(f)}e^{-jd\beta(f)} \tag{9}$$

where γ (f) is the propagation constant, α (f) is the attenuation and β (f) is the phase constant. One can easily see from Fig. 2 and equation (9) that FEXT attenuates by $|H_k\ (d,f)|$ until it reaches to the receiver. On the other hand, NEXT has much effect on transmission because of the close inductance distance to the receiver.

The propagation loss is usually specified in practice as loss per unit length (d=1) and obtained from equation (9) in the following way:

$$L_P(f) = -20\log\left|H(1,f)\right| \approx 8.686\alpha(\mathrm{f}) \tag{10}$$

For pairs that have different propagation constants ($\alpha_1 \neq \alpha_2$) NEXT and FEXT can be computed as functions of attenuation and cable length by using (11) and (12).

$$A_n = -10\log\frac{\omega^2}{(\alpha_1+\alpha_2)}\mathrm{C}_\mathrm{n}^2\left(1\text{-}\mathrm{e}^{-2(\alpha_1+\alpha_2)d}\right) \tag{11}$$

$$A_f = -10\log\omega^2.\left(\frac{\mathrm{C_u}Z_0}{8} - \frac{M}{2Z_0}\right)^2.\mathrm{d} \tag{12}$$

where

$$C_n = \left(\frac{Z_0.C_u}{8} + \frac{M}{2Z_0}\right) \tag{13}$$

As it can be seen from (11) and (12), NEXT and FEXT depend not only on frequency and couplings but also on link lengths. If L>>1km, its effect on NEXT can be neglected.

III. SIMULATIONS AND EXPERIMENTAL RESULTS

With the help of equations derived in Section II numerical expressions for TIA/EIA-568-A worst-case propagation loss and worst-case pair-to-pair NEXT loss at 20°C are given in Table 1 and Table 2 respectively, where f is expressed in MHz and f_0 = 0.772 MHz. The third column in Table 1 gives the temperature dependency of the propagation loss [1].

Table 1. Worst-Case Propagation Loss At 20°C

TIA/EIA Cable	$L_p(f)$ (dB/100km)	Increase Per 1°C	Frequency Range
Category 3	$2.320\sqrt{f}+0.238f+0.000/\sqrt{f}$	1.2%	$0.772 \leq f \leq 16$
Category 4	$2.050\sqrt{f}+0.043f+0.057/\sqrt{f}$	0.3%	$0.772 \leq f \leq 20$
Category 5	$1.967\sqrt{f}+0.023f+0.050/\sqrt{f}$	0.3%	$0.772 \leq f \leq 100$

Table 2. Worst-Case Pair-to-Pair NEXT Loss At 20°C

TIA/EIA Cable	NEXT Loss (dB)	Frequency Range
Category 3	$43-15\log(f/f_0)$	$0.772 \leq f \leq 16$
Category 4	$58-15\log(f/f_0)$	$0.772 \leq f \leq 20$
Category 5	$64-15\log(f/f_0)$	$0.772 \leq f \leq 100$

Plots of the worst-case propagation loss and pair-to-pair NEXT loss for 100 m Category 3, Category 4 and Category 5 cables are given in Fig. 3.

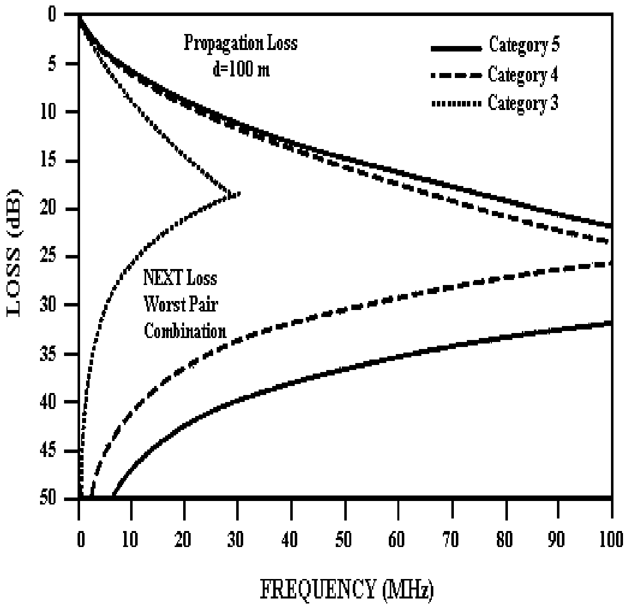

Fig. 3. TIA/EIA-568-A Worst-Case Propagation Loss and Pair-to-Pair NEXT Loss

The graphics in Figs. 4 and 5 give the simulation results for pair-to-pair NEXT loss characteristics for different combinations of twisted pairs in 100 m Category 3 and Category 5 cables, respectively. The smooth curves in these figures are the worst-case pair-to-pair NEXT losses specified in the TIA/EIA-568-A standard.

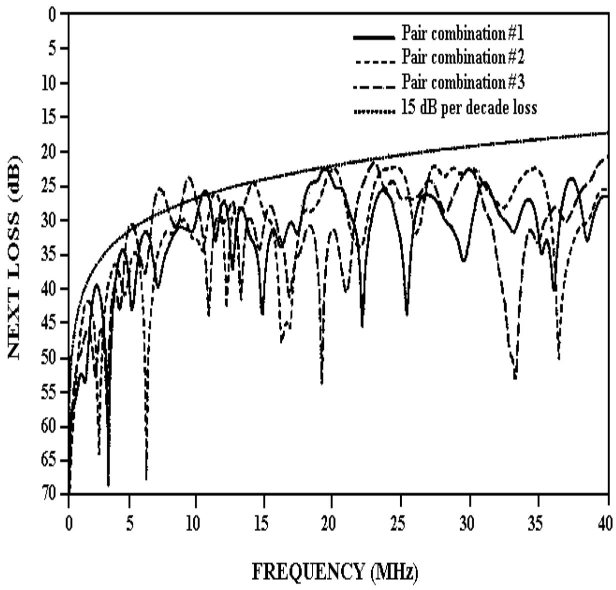

Fig. 4. NEXT Loss Between Pairs of Category 3 Cables

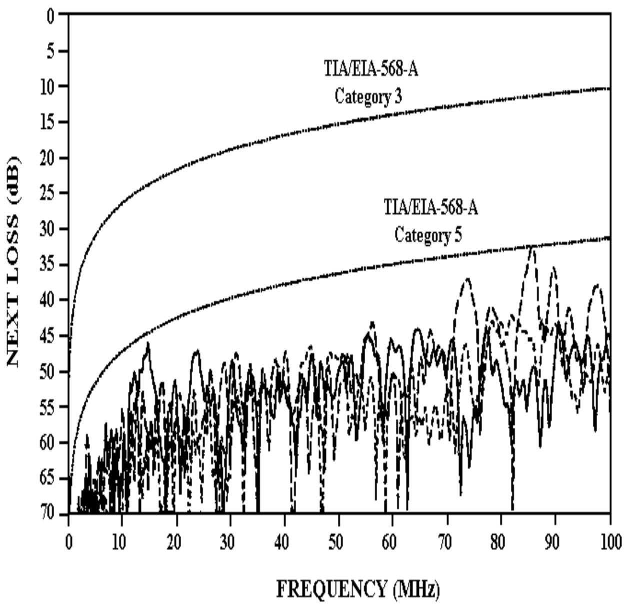

Fig. 5. NEXT Loss Between Pairs of Category 5 Cables

TIA/EIA cable-test methods have two main link definitions [1]. These are the basic link and the channel. Basic links are subsets of the channel and comprise the permanently installed horizontal wiring from the wiring closet cross-connection to the work area outlet and patch cords. The channel link contains every element required to carry data from the wiring closet hub to the desktop PC. For experiments whose results are presented in this section, 90 meters of horizontal UTP cables and 4 meters of patch cords are used in basic link test configurations and 90 meters of UTP cables and 10 meters of end-user patch cords are used in channel link test configurations.

The measured propagation loss values of the channel link and the basic link for various frequencies at 20°C are given in Table 3 and 4, respectively.

Table 3. Maximum Channel Propagation Loss

Frequency (MHz)	Propagation Loss (dB)	
	Category 3	Category 5
1	4.2	2.5
4	7.3	4.5
8	10.2	6.3
10	11.5	7.0
16	14.9	9.2
20		10.3
25		11.4
31.25		12.8
62.5		18.5
100		24.0

Table 4. Maximum Basic Link Propagation Loss

Frequency (MHz)	Propagation Loss (dB)	
	Category 3	Category 5
1	3.2	2.1
4	6.1	4.0
8	8.8	5.7
10	10.0	6.3
16	13.2	8.2
20		9.2
25		10.3
31.25		11.5
62.5		16.7
100		21.6

When the results presented in Table 3 are compared with Fig. 3, it is obvious that measured values are below the worst-case propagation loss values.

Table 5 and 6 give the measured worst pair NEXT loss in channel link and basic link, respectively.

Values in Table 5 show that the tested cables have much better NEXT loss performances than the characteristics shown in Fig. 3.

If Category 3 and Category 5 cables are compared with the help of these experimental results, one can say that UTP-3 cables exhibit higher signal attenuation and significantly lower near-end crosstalk (NEXT) loss than UTP-5 cables. Another important point is the frequency range. UTP-3 cables are limited to 16 MHz while UTP-5 cables can be used up to 100 MHz.

Table 5. Worst Pair NEXT Loss in The Channel Link

Frequency (MHz)	NEXT Loss (dB)	
	Category 3	Category 5
1	39.1	60.0
4	29.3	50.6
8	24.3	45.6
10	22.7	44.0
16	19.3	40.6
20		39.0
25		37.4
31.25		35.7
62.5		30.6
100		27.1

Table 6. Worst Pair NEXT Loss in The Basic Link

Frequency (MHz)	NEXT Loss (dB)	
	Category 3	Category 5
1	40.1	60.0
4	30.7	51.8
8	25.9	47.1
10	24.3	45.4
16	21.0	42.8
20		40.7
25		39.1
31.25		37.6
62.5		32.7
100		29.3

IV. UTP INSTALLATION IN LAN APPLICATIONS

The vast majority of existing local area network (LAN) connections are based on IEEE 802.3 Ethernet standard. Although Ethernet originally supported only coaxial links, since the mid-1980's Ethernet (type 10Base-T) connections using voice grade unshielded twisted pair (UTP Category 3) cables have been available. These allow standard structured cabling to be exploited, providing for easy reconfiguration and management of the LAN and have proved a popular alternative to coaxial connections. By 1990, two thirds of LAN connections were to UTP media.

During the last decade, to provide requirements of distributed processing and high-speed applications new networking standards with high data speeds have been developed. The local networking industry has been highly interested in transceiver technologies for transmission over existing Category 3 cables or newly installed Category 4 or 5 cables because of significant cost advantages over optical links, for which fibres are in most cases yet to be installed. LAN applications supported by cabling standards that are existing and under development are given in Table 7.

Table 7. Cabling Standards- Existing and Under Development

Cable Category	Media Type	Channel Length	Spectral B/W	Applications Supported
Cat 3	UTP	100 m	16 MHz	4 Mb TR, 10Base-T
Cat 4	UTP	100 m	20 MHz	4&16Mb TR, 10Base-T
Cat 5	UTP	100 m	100 MHz	100Base-TX, 1000Base-T
Cat 5e	UTP	100 m	100 MHz	100Base-TX, 1000Base-T
Cat 6	UTP	100 m	250 MHz	1000Base-T
Cat 7	STP	N/A	600 MHz	N/A

Today, running Gigabit Ethernet over copper (1000Base-T) is a growing requirement as organizations begin to saturate some of their Fast Ethernet (100Base-T) segments. Backbones and server connections are the first to fill these 100 Mbps pipes, creating network-wide bottlenecks.

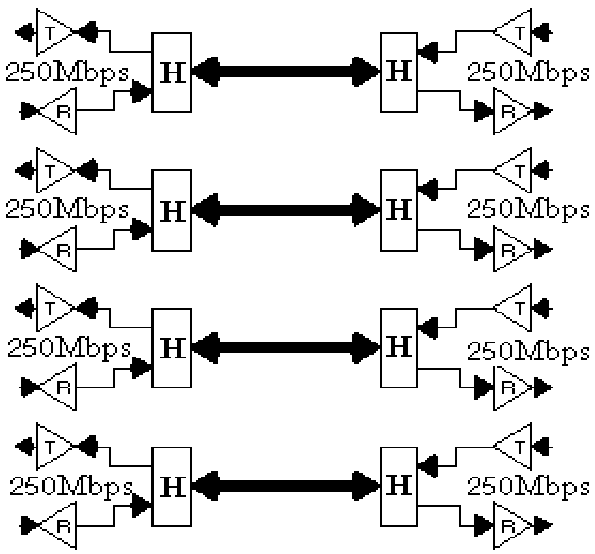

Fig. 6. Data Transmission in 1000Base-T

In order to support full-duplex operation at 1000 Mbps, 1000Base-T Gigabit Ethernet uses four copper pairs to concurrently pump 250 Mbps to each pair as shown in Fig. 6. By comparison, 100Base-TX Fast Ethernet can also support full-duplex operation but it transmits on one pair and receives on a separate pair [3].

Category 5 cable was designed for applications using only one pair (out of four) at a time and 100Base-TX uses only one pair to transmit at 100 Mbps while 100Base-T4 does not support full-duplex operation. Although it seems to adequately support such connections, Category 5 specifications were not designed with concurrent transmission over multiple pairs. As a result, the original Category 5 horizontal installation specifications may not be enough for 1000Base-T applications. A new type of copper cable named enhanced Category 5 (or shortly Category 5e) can support Gigabit Ethernet much better than Category 5 cable. Cat5e tightens some Category 5 parameters such as NEXT, FEXT and return loss and adds several new requirements like power sum NEXT, power sum equal level FEXT. Characteristics of Category 5e are given in Table 8 and 9.

Table 8. Attenuation, NEXT and FEXT Characteristics of Category 5e

Frequency (MHz)	Attenuation (dB/100m)	NEXT (dB) 71-15logf	FEXT (dB/100km) 69-20logf
1	2.0	71	69
4	3.9	62	57
10	6.2	56	49
16	7.8	53	45
20	8.8	51	43
31.25	11.1	49	39
62.5	16.0	44	33
100	20.7	41	29

Table 9. PS-NEXT, PS-ELFEXT and PS-ACR Characteristics of Category 5e

Frequency (MHz)	PS-NEXT (dB) 68-15logf	PS-ELFEXT (dB/100m) 66-20logf	PS-ACR (dB/100km)
1	68	66	66
4	59	54	55
10	53	46	47
16	50	42	42
20	48	40	40
31.25	46	36	34
62.5	41	30	25
100	38	26	17

When attenuation and NEXT characteristics in Table 8 are compared with the values of Table 3 and 5 respectively, it is clear that Category 5e exhibits lower signal attenuation and higher near-end crosstalk (NEXT) loss than Category 5.

In Table 9, power-sum (PS) NEXT measures the crosstalk that three transmitting pairs induce on the fourth pair at the transmission end; power-sum ELFEXT makes this measurement at the far end. Power sum attenuation-to-crosstalk ratios (PS-ACR) represent signal-to-noise measurements that indicate safe operating margin.

Although characteristics of Category 5e are given in a frequency range of 100 MHz in Tables 8 and 9, it can support frequencies up to 200 MHz and can be used in 155 Mbps ATM applications as well as Gigabit Ethernet configurations.

Given its more stringent performance requirements, even Cat 5e cabling has limitations that potentially prevent Gigabit Ethernet from performing reliably. There is no patch cord specification yet, which is scary because 65 percent of all Category 5 patch cords still fail the latest NEXT requirements. Moreover, there is little tolerance for error.

Two new cabling standards called Category 6 and Category 7 are under development. Category 6 will be unshielded twisted pair copper cable with a spectral bandwidth of 250 MHz while Category 7 will be shielded twisted pair (STP) copper cable characterized up to 600 MHz.

V. CONCLUSION

Propagation loss and NEXT have important roles in performance degradation of UTP cables. Category 3 cables have higher attenuation but lower NEXT losses than Category 5 cables and are limited by a frequency range of 16 MHz. Category 5 cables have a frequency range of 100 MHz and can support LAN applications up to 1000Base-T without any problems. But since they were not designed for concurrent transmission over multiple pairs, they can cause some problems in Gigabit Ethernet applications. Category 5e has new characteristics to support gigabit transmission but has little tolerance for error and shows a lack of patch cord specification. Category 6 draft standard hardware is available but is not interoperable. Category 6 would be a requirement for the future TIA 1000Base-TX Gigabit Ethernet and may be the last major advancement in UTP technology since Category 7, which is under development, will be STP.

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[1] TIA/EIA-568-A Standard, the Commercial Building Telecommunications Cabling Standard, 1994.

[2] G. Yılmaz, “ Variation of Pair-to-Pair Near End and Far End Crosstalk Attenuation with Frequency in Symmetrical Telecommunication Cables”, Bulletin of YTU, No. 1996/3-4, pp. 16-29

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