Telecommunication cables

Cables represent transmission mediums having distributed parameters, the internal schematic of a cable segment being presented in figure 1. A cable is characterized by a distributed resistance, R, expressed in Ω/km, a distributed capacitance, C, expressed in nF/km, a distributed inductance, L, expressed in µH/km and by a distributed conductance, G, expressed in µS/km. The length unit is 1km and was chosen due to the relatively large length of the cables used in subscriber loops.

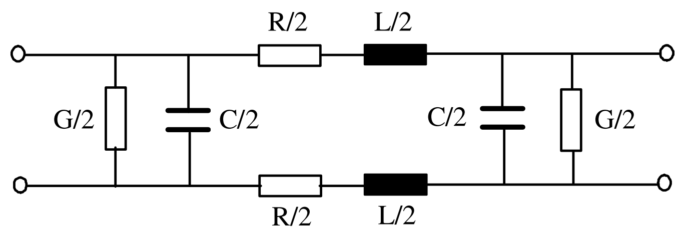

Fig. 1 Equivalent schematic of a cable segment

Some important remarks related to the distributed parameters, called also primary parameters, of the cables are the following: the primary parameters are dependent on the frequency – the distributed resistance and conductance increase with the frequency, the distributed capacitance is constant with frequency, and the distributed inductance decreases with frequency; in the telephone band are important only the distributed resistance and capacitance; the distributed inductance have to be considered at frequencies larger than 30kHz and at frequencies larger than several hundreds of kHz the distributed conductance has to be considered as well.

Based on the primary parameters can be defined other parameters of cables, parameters related to the transfer characteristic of the cable and the impedance matching with external impedances. Two very important parameters, called also secondary parameters, are the characteristic impedance, Z_c, and the propagation constant, γ, parameters given by the following relations:

$$\gamma = \alpha(\omega) + j\beta(\omega) = \sqrt{(R + j\omega L)\cdot(G + j\omega C)} \quad ; \quad Z_c(\omega) = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (1)$$

where α is the attenuation constant of the cable, expressed in Np/km, and β is the phase constant, expressed rad/km. From relation (1) results a double dependence of the attenuation and phase constant on frequency; the secondary parameters depend on frequency and on primary parameters, but the primary parameters also depends on frequency.
Remark: the transformation from Np in dB can be realized according to relation: 1Np=8.68dB;

The importance of the characteristic impedance is the following: if at one end of the cable having the characteristic impedance Z_c it is connected a load impedance having the value Z_c, then the input impedance seen at the other end of the cable is also Z_c, meaning that takes place a „transfer" of the load impedance from one end of the cable to the other end. This aspect is very important if it is required an impedance matching all over the cable (see figure 2).

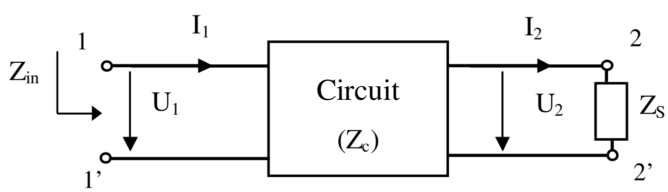

Fig. 2 Impedance matching betwen the cable and the impedances connected to it

Based on the attenuation and phase constant the frequency transfer characteristic, a(ω), can be computed as: $a(\omega) = e^{\alpha(\omega)\cdot l} \cdot e^{j\beta(\omega)\cdot l} = \frac{\overline{U}_1}{\overline{U}_2}$ (2) , where l is the length of cable. If at the input of the cable is applied a sine signal with frequency ω_s, amplitude A_i and phase φ_i, then at the output of the cable is obtained a sine signal having the same frequency, amplitude A_o and phase φ_o, given by:

$$A_o = A_i \cdot e^{-\alpha(\omega_s)\cdot l} \quad ; \quad \varphi_o = \varphi_i - \beta(\omega_s)\cdot l \qquad (3)$$

The cable can be considered as a two-port network, the parameters of this circuit being given by γ and Z_c secondary parameters. For example a two-port network can be characterized by the A parameters (known also as ABCD parameters), in the following way:

$$\begin{aligned} U_1 &= A_{11}\cdot U_2 + A_{12}\cdot I_2 \quad \Rightarrow \quad \begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = [A]\cdot\begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \\ I_1 &= A_{21}\cdot U_2 + A_{12}\cdot I_2 \qquad [A] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \end{aligned} \qquad (4)$$

If the cable is composed of several segments having different A parameters, than the global matrix of A parameters is the product of the individual matrices: $[A] = \prod_{i=1}^{n} [A_i]$ (5)

The A parameters can be computed according to the length of the cable, l, the propagation constant and the characteristic impedance in the following way:

$$[A_i] = \begin{pmatrix} \cosh(\gamma_i \cdot l_i) & Z_i \cdot \sinh(\gamma_i \cdot l_i) \\ \frac{1}{Z_i}\cdot\sinh(\gamma_i \cdot l_i) & \cosh(\gamma_i \cdot l_i) \end{pmatrix} \qquad (6)$$

Aspects concerning the attenuation characteristic of twisted wires

- The characteristics of the twisted wires from the subscriber loops are related mainly to the capacitive and resistive primary parameters, (C/km) and (R/km).
- The law describing the variation of the attenuation with frequency of the twisted wires is given by:

$$a(f)_{dB} = \begin{cases} k_1 \cdot f^{\frac{1}{2}} \; ; \; f < 10kHz \\ k_2 \cdot f^{\frac{1}{4}} \; ; 10kHz < f < 100kHz \\ k_3 \cdot f^{\frac{1}{2}} \; ; \; f > 100kHz \end{cases} \qquad (7)$$

the constants k_x depends on the length and the geometry of the cable and on the temperature;

- in fig. 3 is presented the variation of the attenuation per km in the telephone band of twisted wires having different diameters

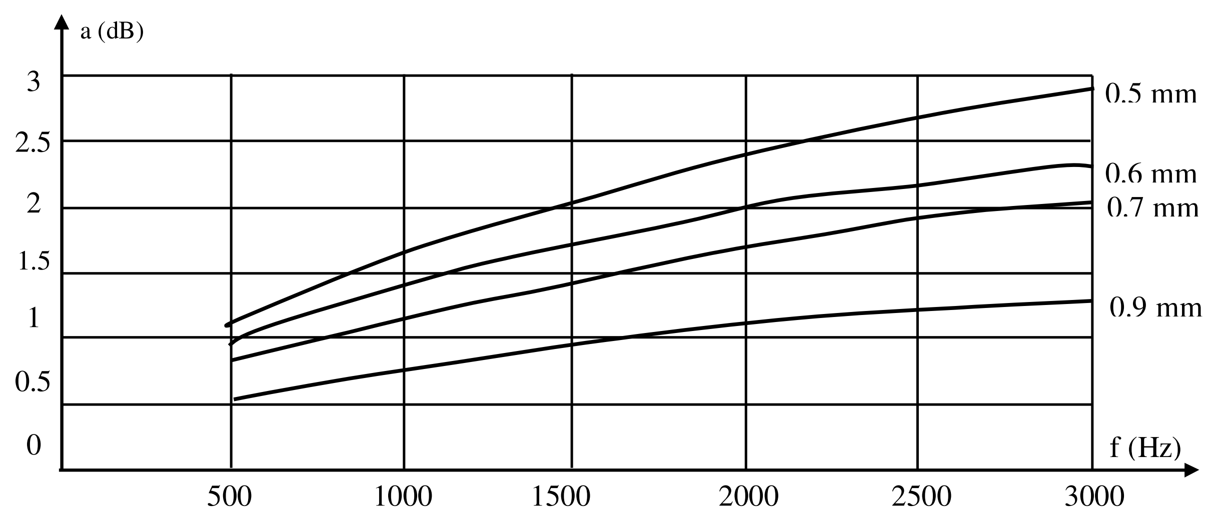

Fig. 3 Variation of the attenuation per km in the telephone band of twisted wires having different diameters

- the attenuation of the cable at a given frequency can be calculated according to the powers of the input and of the output signals, as: $a(f)=V_i^2(f)/V_o^2(f)$ (8) , where V_i is the effective voltage at the input of the cable, and V_o is the effective voltage measured at the output of the cable;
- other empirical relations used to compute the attenuation of the cable with the frequency considering the length of the cable and a temperature of 20°C are:

$$L_{dB}(f)=\left(a\cdot\sqrt{f}+b\cdot f\right)\cdot l \quad (9)$$

the length l is given in km, the parameter *a* depends on the diameter of the wires, and the parameter *b* depends on the insulation of the wires.

- BKMA cable for aerial circuits

$$L_{dB}(f)=\left(21\cdot\sqrt{f}+0.3\cdot f\right)\cdot l \quad (10)$$

  the length l is expressed in km

- UTP CAT 3 cable, "worst case" characteristic, l=100m

$$L_{dB}(f)=\left(2.32\cdot\sqrt{f}+0.238\cdot f\right) \quad (11)$$

- UTP CAT 5 cable, "worst case" characteristic, l=100m

$$L_{dB}(f)=\left(1.967\cdot\sqrt{f}+0.023\cdot f+\frac{0.05}{\sqrt{f}}\right) \quad (12)$$

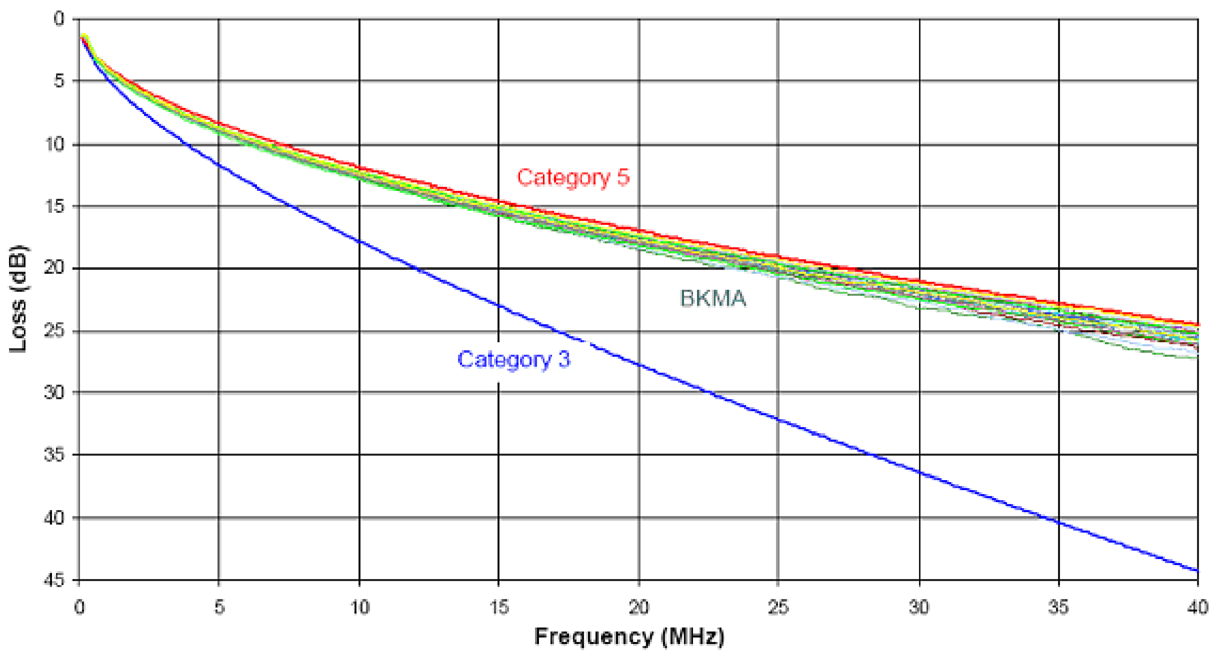

Fig. 4 Variation of the attenuation with frequency for BKMA, CAT 3 and CAT 5 cables having a length of 180m and a temperature of 20°C

Linear crosstalk noise – refers to the unwanted transfer of a useful signal from a circuit to another circuit; could be an intelligible signal generating the loss of confidentiality;

- Noise signals having discrete spectrum are generated by inducing in the circuit of unwanted deterministic signals from other circuits or systems; such noise has a stationary characteristic, a typical example being the power grid induced noise;

- The crosstalk phenomenon takes place between the neighbor pairs of the same cable in two fundamental ways, see fig. 5:

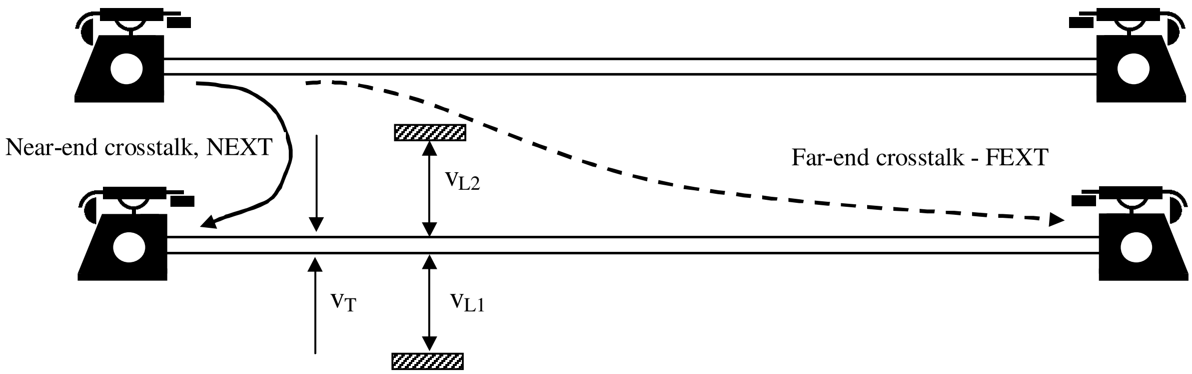

Fig. 5 Main types of crosstalk

- The main causes which generate the crosstalk phenomenon are: capacitive couplings between neighbor pairs and imperfect balancing of the circuits relatively to the ground (earth).
  - On a cable composed of twisted wires can be identified two types of voltages: a transversal (or differential) voltage v_T between two wires – this represents the useful signal, and the longitudinal voltages v_{L1} and v_{L2} between each wire and the ground (earth) – represent the parasitic signals induced by capacitive couplings from different sources – see fig. 5 – ideally the difference between the longitudinal signals is zero, situation in which we do not have an unwanted transversal component.
  - In fig. 6 is represented the situation in which a signal source v (for example the power grid) is coupled through parasitic capacitances C_{c1} and C_{c2} with the two wires of the cable. In this situation two longitudinal voltages between the two wires and the ground, v_{L1} and $v_{L2,}$ are generated, voltages given by the relations:

$$v_{L1} = v_{MC} + \frac{v_d}{2} \; ; \; v_{L1} = v_{MC} - \frac{v_d}{2}$$

$$v_{MC} = \frac{v_{L1} + v_{L2}}{2} \; ; \; v_d = v_{L1} - v_{L2} \tag{13}$$

where v_{MC} is the common mode voltage, and v_d is the differential unwanted noise voltage.

  - The situation described in fig. 6 represents the longitudinal-transversal coupling, and the ratio, expressed in dB, between the longitudinal (common mode) and the differential (transversal) voltages represents the *Common Mode Rejection Ratio*, RRMC

$$RRMC = 20 \cdot lg\left(\frac{V_{MC}}{Vd}\right)[dB] \tag{14}$$

  - If the capacitances C_{c1} and C_{c2} are equal and the inductances of the power supply bridge are also equal, then the longitudinal voltages v_{L1} and v_{L2} are equal and the transversal (differential) noise voltage is zero.
  - The situation presented in fig. 6 is characteristic to the coupling between the power grid and the twisted pairs – power grid noise is induced in the telephone channel.

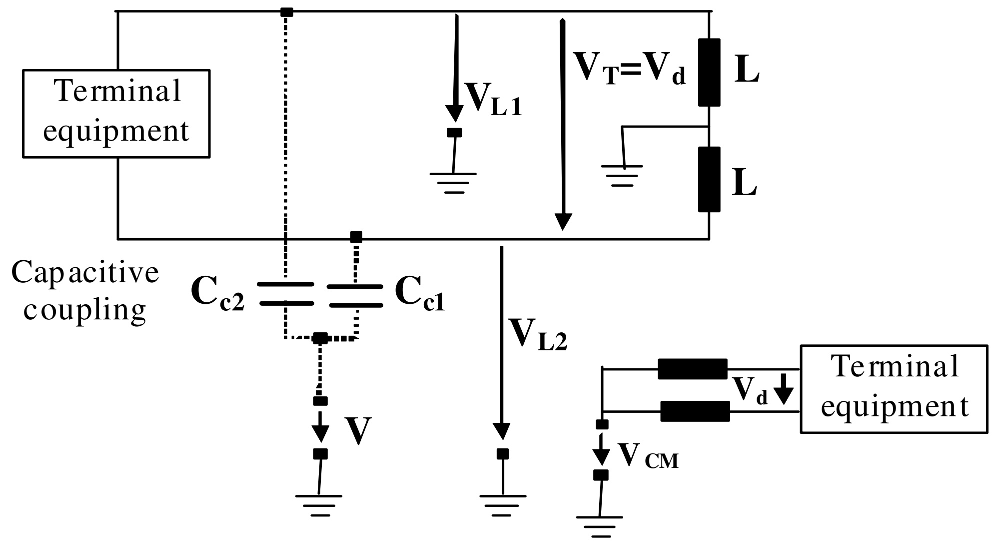

Fig. 6 Longitudinal – transversal capacitive coupling

- figure 7 presents the situation in which the neighbor twisted pairs are coupled by parasitic capacitances; crosstalk is generated between the neighbor channels; signaling tones can be induced from one channel to another channel.

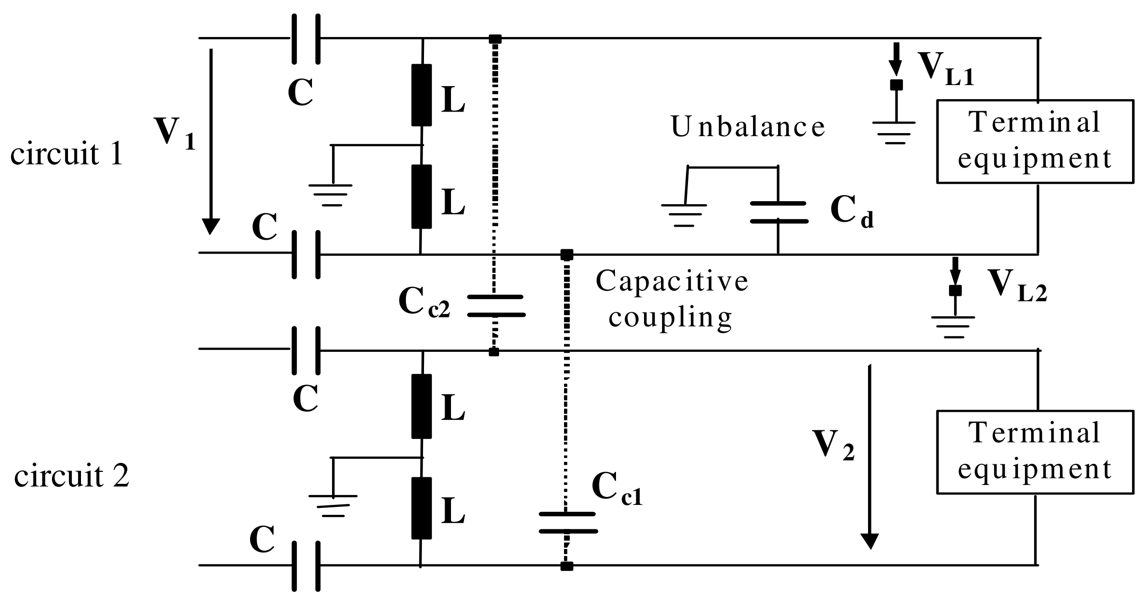

Fig. 7 Transversal – longitudinal and longitudinal – transversal coupling

- In the situation presented in fig. 7 the first circuit transmits the differential signal v_1, which is the useful signal, and in this circuit an unbalance is generated by the parasitic capacitance C_d; if this capacitance is missing the longitudinal voltages v_{L1} and v_{L2} are identical, but in the presence of the C_d capacitance these voltages are not identical anymore – a transversal-longitudinal coupling appears between the source generating the signal v_1 and the wires of circuit 1.
  - Due to the parasitic capacitances C_{c1} and C_{c2} a longitudinal-transversal coupling appears between circuit 1 and 2, meaning between the signal sources represented by v_{L1} and v_{L2} and the wires of circuit 2 – an unwanted transversal (differential) voltage, v_2, appears in the second circuit, even if the capacitances C_{c1} and C_{c2} are identical.

- The transversal-longitudinal coupling is characterized by the crosstalk attenuation:

$$a_{cross} = 20 \cdot lg\left(\frac{V_1}{V_2}\right)[dB] \tag{15}$$

- Other causes generating crosstalk are the following: inductive coupling between the pairs (it is reduced by twisting the wires), parasitic couplings between modules, capacitive and inductive coupling between the pathways of printed boards and between electronic components;
- The mathematical modeling of the crosstalk phenomenon (Near End Crosstalk – NEXT and Far End Crosstalk - FEXT) due to the coupling between the pairs of a cable.

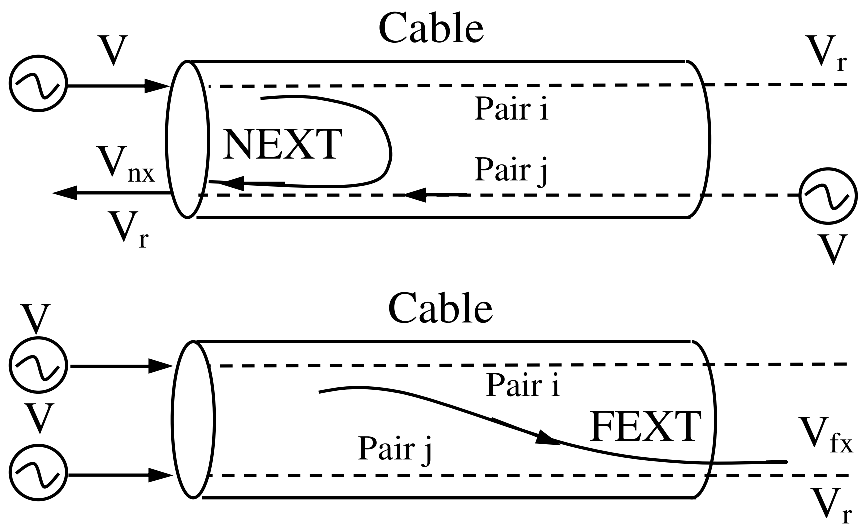

Fig. 8 NEXT and FEXT between the pairs of a cable

- The NEXT and FEXT component of the crosstalk can be characterized by the $A_{nx}(f)$ and $A_{fx}(f)$ frequency dependent crosstalk attenuations – the mentioned parameters can be computed according: $A_{nx}(f) = \frac{V^2(f)}{V_{nx}^2(f)}$; $A_{fx}(f) = \frac{V^2(f)}{V_{fx}^2(f)}$ (16)
- If several pairs are interfering with pair j then the sum of the NEXT and FEXT interference signal powers is given by: $V_{nx}^2 = \sum_{i \neq j} V_{nx,j}^2$; $V_{fx}^2 = \sum_{i \neq j} V_{fx,j}^2$ (17)
- If it is considered a cable with k pairs out of which n pairs are interfering, at high frequencies (>500kHz), the crosstalk attenuations expressed in dB have the following expressions:

$$\begin{aligned} A_{nx,dB}(f) &= K_{nx} - 15 \cdot \ln(f) + 6 \cdot \ln(m/n) \\ A_{fx,dB}(f) &= K_{fx} - 20 \cdot \ln(f) - 10 \cdot \ln(f) + 6 \cdot \ln(m/n) \\ m &= k - 1 \end{aligned} \tag{18}$$

K_{nx} and K_{fx} are crosstalk coupling constants and depend on the UTP cable parameters and m is the number of interference sources.

- BKMA cable for aerial circuits

$$\begin{aligned} A_{nx,dB}(f) &= 40.3 - 15 \cdot \ln(f) + 6 \cdot \ln(m/n) \\ A_{fx,dB}(f) &= 35.6 - 20 \cdot \ln(f) - 10 \cdot \ln(d) + 6 \cdot \ln(m/n) \end{aligned} \tag{19}$$

the distance d is expressed in km;

- CAT 3 UTP cable, "worst case" characteristic, d=100m

$$A_{nx,dB}(f) = 41.3 - 15 \cdot \ln(f)$$
$$A_{fx,dB}(f) = 51 - 20 \cdot \lg(f/0.772) \tag{20}$$

- CAT 5 UTP cable, "worst case" characteristic, d=100m

$$A_{nx,dB}(f) = 62.3 - 15 \cdot \lg(f)$$
$$A_{fx,dB}(f) = 63 - 20 \cdot \lg(f/0.772) \tag{21}$$

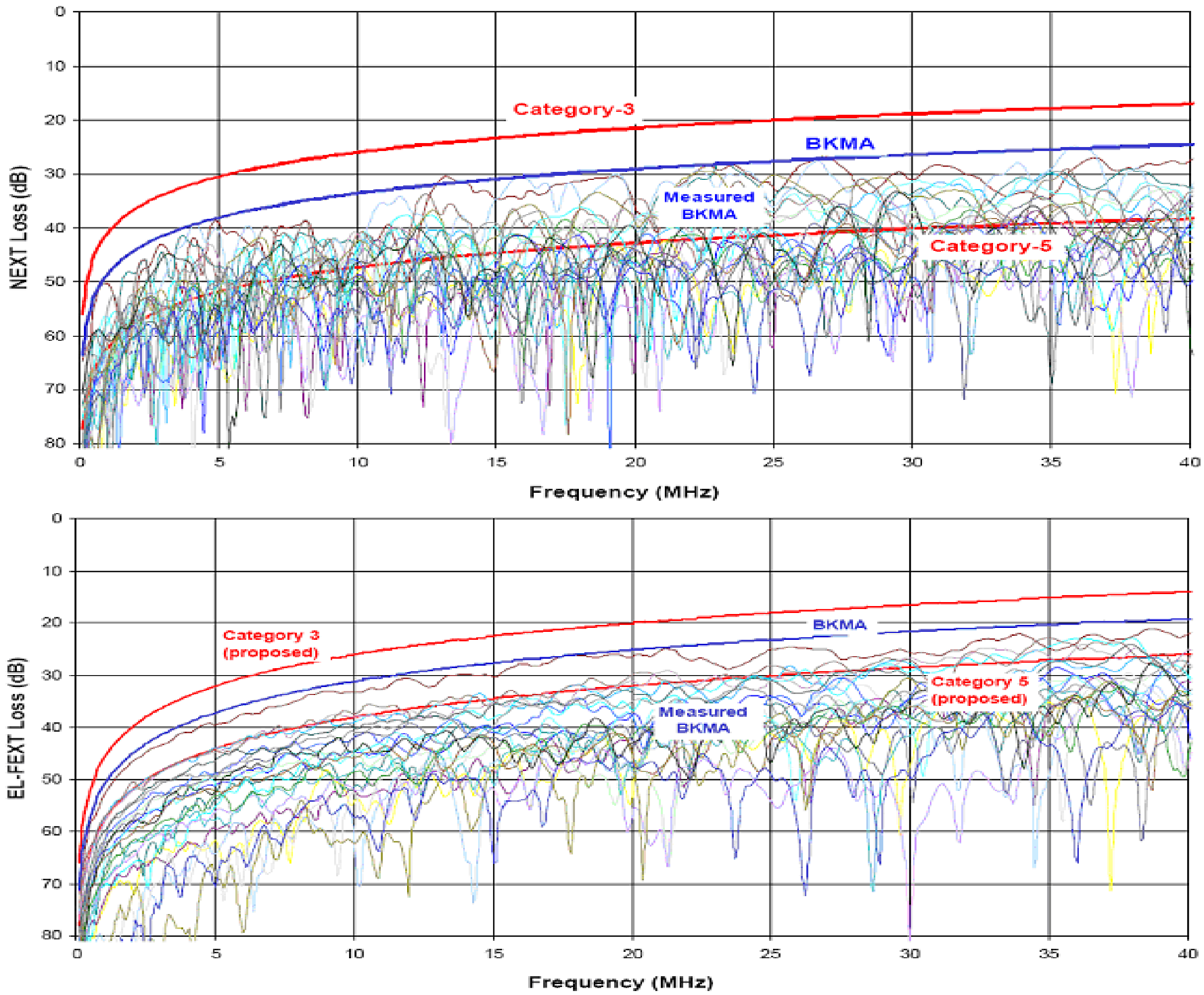

Fig. 9 Variation with frequency of the pair to pair NEXT and FEXT attenuation ;
EL-FEXT = FEXT – Attenuation (or loss)

- Other useful relations for the spectral density of the pair to pair crosstalk (interference) signals:

$$Next(f) = S(f) \cdot K_N \cdot f^{1.5}$$
$$Fext(f) = S(f) \cdot K_F \cdot f^2 \cdot l \cdot |H(f)|^2 \tag{22}$$

where f is the frequency in Hz, l is the length in feet, K_N is a constant equal with $8.536 \cdot 10^{-15}$, K_F is a constant equal with $7.74 \cdot 10^{-21}$, S(f) is the spectral density of the interference signal, H(f) is the channel transfer function.

- If there are n identical interference sources the summing of the interferences can be performed in the following way:

$$Next[f,n] = S(f) \cdot K_N \cdot f^{1.5} \cdot n^{0.6}$$
$$Fext[f,n] = S(f) \cdot K_F \cdot f^2 \cdot l \cdot |H(f)|^2 \cdot n^{0.6} \quad (23)$$

The value of 0.6 (the value of power of n) is selected empirically – is valid for cables used in USA networks. The cables of European network have an exponent of 0.7 or 0.8. The relation is more precise for a large number of self interfering signals.

- Other interference summation formulas are more complex.
- As an example are presented some of the CAT 5 UTP cable specifications:
  - Capacitance: 14 pF/ft;
  - Conductor: 24 AWG solid cooper wire;
  - Frecvency: up to 100MHz;
  - Impedance: 100 ± 15 Ω;

Test method	Maximum	Minimum
DC resistance, (Ω/100m)	9.38	
DC resistance unbalance (%)	5	
Impedanță (Ω) 1 – 100MHz	100 ± 15	
	Attenuation dB/100m	NEXT crosstalk dB/100m
0.772 MHz	1.833	64
1.000 MHz	2.100	62
4.000 MHz	4.333	53
8.000 MHz	6.000	48
10.000 MHz	6.666	47
16.000 MHz	8.333	44
20.000 MHz	9.333	42
25.000 MHz	10.666	41
31.250 MHz	12.000	40
62.500 MHz	17.333	35
100.000 MHz	22.333	32

Table. 1 Some specifications related to UTP CAT 5 cable

The internal structure and parameters of the telecommunication cables used in practice

Urban telecommunication cables

The urban telecommunication cables are used in the cabling of urban areas and are intended to work at voltages smaller than 150V. There are subscriber loop cables (subscriber – exchange connection) and trunk cables (connections between exchanges).

From the point of view of installation the urban telecommunication cables can be:

- Aerial cables installed on poles or building walls;
- Underground cables lying in buried ducts.

Structure of telecommunication cables

The general internal structure of a classical telecommunication cable is presented in fig. 10.

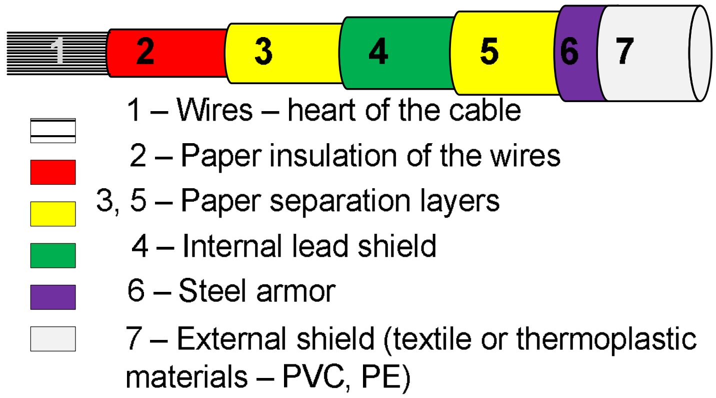

Figure 10 The classical structure of telecommunication cables

Remarks: in the case of the modern telecommunication cables the insulation of the wires is made of plastic; instead of layers of paper are used plastic foils, and the external metallic shield (or sheath) is replaced by a layer of plastic or rubber (special rubberized plastic). To ensure some protection against external interferences can be used a metallic (aluminum) foil located beneath the external plastic sheath. A newer technology employs a special gel to fill the spaces between the wires of the cable. In such a way the water cannot get inside the cable even it is laying in a high humidity environment. The wires composing the heart of the cable are twisted to reduce the electromagnetic couplings (crosstalk).

Electrical characteristics

The characteristics important in practice are:

- **Electrical resistance** – measured on the physical circuit (pair) in cc at 20ºC. Some usual values are: 57Ω/km (2×0.9mm), 284Ω/km (2×0.4mm).
- **Insulation resistance** of each wire relatively to the other wires connected to the shield (if we have metallic shield) (5000MΩ/km).
- **Nominal capacitance** – measured at 800Hz between a pair and the other pairs connected to the shield (40-60nF – typical values).
- **Attenuation** (at 800Hz) – can be calculated by using:

  $$\alpha = \sqrt{\frac{\omega RC}{2}}\,[Np/km] \qquad (24)$$

  where R represents the electrical resistance of the pair in Ω/km, C represents the nominal (or maximal) capacitance of the pair expressed in F/km, and ω represents the angular speed in rad/sec.
- **Breakthrough voltage** – the cable has to support this voltage without breakthrough of the insulation, for one minute:
  - 1500V applied between the metallic shield connected to the ground and all the wires connected together;
  - 500V applied between the group of the first wire of all pairs (wires of the group connected together) and the group of the second wire of all pairs (also connected together).

Long distance telecommunication cables

Are intended for long distance trunk connections and have to support a maximum voltage of 250V. The copper wires are twisted using a given step in DM quads (Diesel horst – Martin or double pair quads), or S (star) quads.

The long distance cables could be low or high frequency cables.

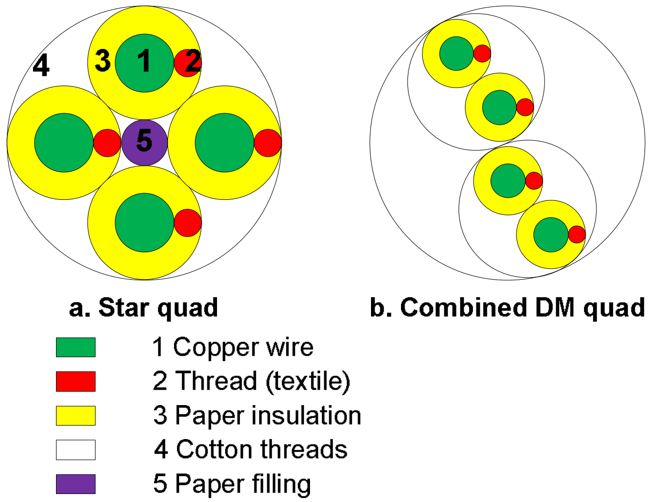

Figure 11 Quads of physical circuits

Remarks:
The insulation of modern cables is plastic. See the previous remarks.
Such cables can be used for transmission of the PCM frames or of other PDH frames.

Electrical characteristics

- **Electrical resistance** of a pair measured in cc at 20ºC. Some typical values 57Ω/km (2×0.9mm), 32Ω/km (2×1.2mm).
- **Insulation resistance** is measured between a wire of the cable and all other wires connected together and connected to the metallic shield; has to be at least 10000Ω/km.
- **Breakthrough voltage** – the cable has to support this voltage without breakthrough of the insulation, for one minute:
    - 2000V (50Hz) applied between the metallic shield connected to the ground and all the wires connected together;
    - 500V applied between a wire (any wire) of a quad and the other wires of the quad connected together.
- **Nominal capacitance** measured at 800Hz between the wires of one pair and the other wires connected together and connected to the metallic shield. Some typical values are 26.5nF/km for high frequency cables and 38.5nF/km for low frequency cables.
- **Attenuation constant** is the real part of the propagation constant and has as typical values:
    - 75mNp/km at f = 800Hz for low frequency circuits;
    - 240mNp/km at f = 120kHz for high frequency circuits;
    - 350mNp/km at f = 240kHz for high frequency circuits.