



BSI Standards Publication

Multicore and symmetrical pair/quad cables for digital communications —

Part 1-2: Electrical transmission characteristics and test methods of symmetrical pair/quad cables

National foreword

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TECHNICAL REPORT

**Multicore and symmetrical pair/quad cables for digital communications –
Part 1-2: Electrical transmission characteristics and test methods of
symmetrical pair/quad cables**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

MULTICORE AND SYMMETRICAL PAIR/QUAD CABLES FOR DIGITAL COMMUNICATIONS – PART 1-2: ELECTRICAL TRANSMISSION CHARACTERISTICS AND TEST METHODS OF SYMMETRICAL PAIR/QUAD CABLES

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IEC 61156-1-2, which is a technical report, has been prepared by subcommittee 46C: Wires and symmetric cables, of IEC technical committee 46: Cables, wires, waveguides, R.F. connectors, R.F. and microwave passive components and accessories.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
46C/853/DTR	46C/889/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61156 series, under the general title: *Multicore and symmetrical pair/quad cables for digital communications*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

MULTICORE AND SYMMETRICAL PAIR/QUAD CABLES FOR DIGITAL COMMUNICATIONS –

PART 1-2: ELECTRICAL TRANSMISSION CHARACTERISTICS AND TEST METHODS OF SYMMETRICAL PAIR/QUAD CABLES

1 Scope

This technical report is a revision of the symmetrical pair/quad electrical transmission characteristics present in IEC 61156-1:2002 (Edition 2) and not carried into IEC 61156-1:2007 (Edition 3).

This technical report includes the following topics from IEC 61156-1:2002:

- the characteristic impedance test methods and function fitting procedures of 3.3.6;
- Annex A covering basic transmission line equations and test methods;
- Annex B covering the open/short-circuit method;
- Annex C covering unbalance attenuation.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-726, *International Electrotechnical Vocabulary – Part 726: Transmission lines and waveguides*

 IEC 60169-15, *Radio-frequency connectors – Part 15: R.F. coaxial connectors with inner diameter of outer conductor 4,13 mm (0,163 in) with screw coupling – Characteristic impedance 50 ohms (Type SMA)* 

IEC 61156-1:2007, *Multicore and symmetrical pair/quad cables for digital communications – Part 1: Generic specification*

 IEC 61169-16, *Radio-frequency connectors – Part 16: Sectional specification – RF coaxial connectors with inner diameter of outer conductor 7 mm (0,276 in) with screw coupling – Characteristics impedance 50 ohms (75 ohms) (type N)* 

IEC/TR 62152, *Background of terms and definitions of cascaded two-ports*

3 Terms, definitions, symbols, units and abbreviated terms

3.1 Terms and definitions

 For the purposes of this document, the terms and definitions given in IEC 60050-726, IEC TR 62152 and the following apply: 

3.1.1

single-ended

measurement with respect to a fixed potential, usually ground 

3.2 Symbols, units and abbreviated terms

For the purposes of this document, the following symbols, units and abbreviated terms apply.

Transmission line equation electrical symbols and related terms and symbols:

R	pair resistance (Ω/m)
L	pair inductance (H/m)
G	pair conductance (S/m)
C	pair capacitance (F/m)
α	attenuation coefficient (Np/m)
β	phase coefficient (rad/m)
γ	propagation coefficient (Np/m , rad/m)
v_P	phase velocity of cable (m/s)
v_G	group velocity of cable (m/s)
τ_P	phase delay time (s/m)
τ_G	group delay time (s/m)
Z_C	complex characteristic impedance, or mean characteristic impedance if the pair is homogeneous or free of structure (also used to represent a function fitted result) (Ω)
$\angle Z_C$	angle of the characteristic impedance in radians
Z_∞	high frequency asymptotic value of the characteristic impedance (Ω)
l	length (m)
j	imaginary denominator
Re	real part operator for a complex variable
Im	imaginary part operator for a complex variable
ω	radian frequency (rad/s)
f	frequency (Hz)
R'	first derivative of R with respect to ω
C'	first derivative of C with respect to ω
L'	first derivative of L with respect to ω
R_0	d.c. resistance of a round solid wire with radius r (Ω/m)
R_C	constant with frequency component of resistance which is about 1/4 of the d.c. resistance (Ω/m)
R_S	square-root of frequency component of resistance (Ω/m)
L_E	external (free space) inductance (H/m)
L_I	internal inductance whose reactance equals the surface resistance at high frequencies (H/m)
σ	specific conductivity of the wire material (S/m)
ρ	resistivity of the wire material (Ω/m^2)
μ	permeability of the wire material (H/m)
r	radius of the wire (m)
δ	skin depth (not to be confused with the dissipation factor $\tan \delta$) (m)

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

$\tan \delta$	dissipation factor $\tan \delta = G/(\omega C)$
q	forward echo coefficient at the far end of the cable at a resonant frequency
p	reflection coefficient measured from the near end of the cable at a resonant frequency, $p = 10^{-PSRL/20} = \left \frac{Z_{CM} - Z_C}{Z_{CM} + Z_C} \right $
A_Q	forward echo attenuation at a resonant frequency (dB) $A_Q = -20 \log q $
$PSRL$	structural return loss at a resonant frequency (dB) $PSRL = -20 \log p $
K	$= 2\alpha l - 1$ when $2\alpha l \gg 1$ (Np)
A_Q	$= 2 \times PSRL - 20 \log(2\alpha l - 1)$ (dB) where $2\alpha l$ is in Np
Z_{OC}	complex measured open circuit impedance (Ω)
Z_{SC}	complex measured short circuit impedance (Ω)
Z_{CM}	characteristic impedance as measured (with structure) (Ω) $Z_{CM} = \sqrt{Z_{SC} Z_{OC}}$
Z_{MEAS}	complex measured impedance (open or short) (Ω)
Z_{IN}	input impedance of the cable when it is terminated by Z_L (Ω)
Z_{OUT}	output impedance of the cable when the input of the cable is terminated by Z_G (Ω)
Z_{CN}	nominal characteristic impedance of a cable and is the specified Z_C value at a given frequency with tolerance and the structural return loss SRL limits in dB in a frequency range (Ω)
Z_N	nominal (reference) impedance of the link and/or terminals (the system) between which the cable is operating (Ω)
Z_R	(nominal) reference impedance that is used in measurement. Normally (for actual return loss results), $Z_R = Z_N$. When using a return loss measurement to approximate SRL , it is practical to choose Z_R to give the best balance in the given frequency range (Ω)
Z_T	terminated impedance measurement made with the opposite end of the cable pair terminated in the reference impedance Z_R (Ω)
ζ	reflection coefficient measured in the terminated measurement method $\zeta = \frac{Z_R - Z_C}{Z_R + Z_C}$
Z_G	termination at the cable input when defining the output impedance of the cable Z_{OUT} (Ω)
Z_L	termination at the cable output when defining the input impedance of the cable Z_{IN} (Ω)
L_0, L_1, L_2, L_3	least squares fit coefficients for angle of the characteristic impedance
K_0, K_1, K_2, K_3	least squares fit coefficients of the characteristic impedance
$ Z_C $	fitted magnitude of the characteristic impedance (Ω)

$ Z_{CM} $	measured magnitude of the characteristic impedance (Ω)
$\angle(V_{1N})$	input angle relative to a reference angle in radians
$\angle(V_{1F})$	output angle relative to the same reference angle in radians
k	multiple of 2π radians
S_{11}	reflection coefficient measured with an S parameter test set
RL	return loss (dB)
SRL	structural return loss (dB)

Attenuation unbalance electrical symbols:

TA	transverse asymmetry
LA	longitudinal asymmetry
R_1, R_2	resistance of one conductor per unit length (Ω)
L_1, L_2	inductance of one conductor per unit length (H)
C_1, C_2	capacitance of one conductor to earth (F)
G_1, G_2	conductance of one conductor to earth (S)
α_u	unbalance attenuation (dB)
T_u	unbalance coupling transfer function
Z_{com}	characteristic impedance of the common-mode circuit (Ω)
Z_{diff}	characteristic impedance of the differential-mode circuit (Ω)
Z_{unbal}	unbalance impedance (Ω)
ℓ	length of transmission line (m)
x	length coordinate (m)
γ_{com}	propagation factor of the common-mode circuit (Np/m, rad/m)
γ_{diff}	propagation factor of the differential-mode circuit (Np/m, rad/m)
α_{diff}	operational differential-mode attenuation of the cable (dB)
α_{com}	operational common-mode attenuation of the cable (dB)
ΔR	resistance unbalance of the sample length (Ω)
ΔL	inductance unbalance of the sample length (H)
ΔC	capacitance unbalance to earth (F)
ΔG	conductance unbalance to earth (S)
S	summing function
U_{diff}	voltage in the differential-mode circuit (V)
U_{com}	voltage in the common-mode circuit (V)
n, f	index to designate the near end and far end, respectively

4 Basic transmission line equations

4.1 Introduction

A review of the relationships between the propagation coefficient and characteristic impedance and the primary parameters R , L , G and C is useful here. Characteristic impedance is commonly thought of as being a magnitude quantity. While this concept may suffice for high frequency applications, this quantity is actually a complex one consisting of real and imaginary components or magnitude and angle. The associated propagation coefficient is readily viewed as being complex, consisting of the real attenuation and imaginary phase

coefficient components. The four secondary components are readily related to the primary components. Frequency dependence of these parameters is also developed.

The cable pair parameters are represented as frequency domain dependent quantities. The measurement methods are based on frequency domain techniques. Measurement methods based on time domain techniques and combinations of time and frequency while useful in many cases are not covered here. The present-day availability of excellent frequency domain equipment such as the network analysers and impedance meters supports the frequency domain approach.

4.2 Characteristic impedance and propagation coefficient equations

4.2.1 General

The frequency domain of the complex characteristic impedance Z_C relates to the primary parameters as:

$$Z_C = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (1)$$

The propagation coefficient, γ , relates to the primary parameters as:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (2)$$

4.2.2 Propagation coefficient

4.2.2.1 Attenuation and phase coefficients

Equation (2) is separated into its real and imaginary parts, the attenuation coefficient α and the phase coefficient β :

$$\alpha = \sqrt{-\frac{1}{2}(\omega^2 LC - RG) + \frac{1}{2}\sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)}} \quad (3)$$

$$\beta = \sqrt{\frac{1}{2}(\omega^2 LC - RG) + \frac{1}{2}\sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)}} \quad (4)$$

Further, by factoring out $\omega\sqrt{LC}$ we obtain:

$$\beta = \omega\sqrt{LC} \sqrt{\frac{1}{2}\left(1 - \frac{R}{\omega L} \frac{G}{\omega C}\right) + \frac{1}{2}\sqrt{\left(1 + \frac{R^2}{\omega^2 L^2}\right)\left(1 + \frac{G^2}{\omega^2 C^2}\right)}} \quad (5)$$

It can be shown that:

$$\alpha\beta = \omega\sqrt{LC} \left(\frac{R}{2} \sqrt{\frac{C}{L}} \right) \quad (6)$$

4.2.2.2 Equations useful at high frequencies

From Equations (5) and (6) we can solve for α and thus obtain for α and β the following expressions, valid within the entire frequency range:

$$\alpha = \frac{\frac{R}{2} \sqrt{\frac{C}{L}} + \frac{G}{2} \sqrt{\frac{L}{C}}}{\sqrt{\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}}} \quad (7)$$

$$\beta = \omega \sqrt{LC} \sqrt{\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \quad (8)$$

Equations (7) and (8) are well suited for evaluation of high frequencies.

4.2.2.3 Equations useful at low frequencies

For low frequency evaluations, the expressions given by Equations (9) and (10) are suitable.

$$\alpha = \sqrt{\frac{\omega RC}{2}} \sqrt{\left(\frac{G}{\omega C} - \frac{\omega L}{R} \right) + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \quad (9)$$

$$\beta = \sqrt{\frac{\omega RC}{2}} \sqrt{\left(\frac{\omega L}{R} - \frac{G}{\omega C} \right) + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \quad (10)$$

4.2.3 Characteristic impedance

4.2.3.1 Real and imaginary parts

The characteristic impedance Z_C can also be separated into its real and imaginary parts as developed in Equations (11) and (12).

$$Z_C = \text{Re } Z_C + j \text{Im } Z_C = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \frac{\alpha + j\beta}{G + j\omega C} \quad (11)$$

$$Z_C = \frac{\frac{1}{\omega C} \left[\left(\beta + \frac{G}{\omega C} \alpha \right) - j \left(\alpha - \frac{G}{\omega C} \beta \right) \right]}{1 + \frac{G^2}{\omega^2 C^2}} \quad (12)$$

4.2.3.2 Equations useful at high frequencies

After substituting Equations (7) and (8) into Equation (12), the real and imaginary parts of the characteristic impedance are obtained as given in Equations (13) and (14) respectively. These are well suited for simplification (see 4.3) at high frequencies:

$$\text{Re } Z_C = \frac{\sqrt{\frac{L}{C}} \left[\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)} \right]}{\left(1 + \frac{G^2}{\omega^2 C^2} \right) \sqrt{\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}}} \quad (13)$$

$$-Im Z_C = \frac{\frac{R}{2\omega\sqrt{LC}} + \frac{G}{2\omega C} \sqrt{\frac{L}{C}} - \frac{G}{\omega C} \sqrt{\frac{L}{C}} \left[\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)} \right]}{\left(1 + \frac{G^2}{\omega^2 C^2} \right) \sqrt{\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}}} \quad (14)$$

4.2.3.3 Equations useful at low frequencies

On the other hand, by substituting Equations (9) and (10) into Equation (12), the real and imaginary parts given in Equations (15) and (16) respectively are obtained. These are useful for simplification in the low frequency range:

$$Re Z_C = \frac{\sqrt{\frac{R}{2\omega C}} \left[\sqrt{\frac{\omega L}{R} - \frac{G}{\omega C} + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} + \frac{G}{\omega C} \sqrt{\frac{G}{\omega C} - \frac{\omega L}{R} + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \right]}{\left(1 + \frac{G^2}{\omega^2 C^2} \right)} \quad (15)$$

$$-Im Z_C = \frac{\sqrt{\frac{R}{2\omega C}} \left[\sqrt{\frac{G}{\omega C} - \frac{\omega L}{R} + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} - \frac{G}{\omega C} \sqrt{\frac{\omega L}{R} - \frac{G}{\omega C} + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \right]}{\left(1 + \frac{G^2}{\omega^2 C^2} \right)} \quad (16)$$

4.2.4 Phase and group velocity

The phase propagation time (per unit length) is:

$$\tau_P = \frac{\beta}{\omega} \quad (17)$$

By introducing β from Equations (8) and (10), we obtain:

$$\tau_P = \sqrt{LC} \sqrt{\frac{1}{2} \left(1 - \frac{R}{\omega L} \frac{G}{\omega C} \right) + \frac{1}{2} \sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \quad (18)$$

and

$$\tau_P = \sqrt{\frac{RC}{2\omega}} \sqrt{\left(\frac{\omega L}{R} - \frac{G}{\omega C} \right) + \sqrt{\left(1 + \frac{\omega^2 L^2}{R^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \quad (19)$$

The group propagation time (per unit length) is:

$$\tau_G = \frac{d\beta}{d\omega} \quad (20)$$

$$\tau_G = \frac{\beta}{\omega} + \frac{1}{2} \left(\frac{L'}{L} + \frac{C'}{C} \right) \beta + \frac{\omega^2 LC}{4\beta} \left[\left(-\frac{G}{\omega C} + \frac{\frac{R}{\omega L} \left(1 + \frac{G^2}{\omega^2 C^2} \right)}{\sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \right) \frac{d \left(\frac{R}{\omega L} \right)}{d\omega} \right] + \left[\left(-\frac{R}{\omega L} + \frac{\frac{G}{\omega C} \left(1 + \frac{R^2}{\omega^2 L^2} \right)}{\sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \right) \frac{d \left(\frac{G}{\omega C} \right)}{d\omega} \right] \quad (21)$$

The phase and group velocities are, respectively,

$$v_P = \frac{1}{\tau_P} \quad (22)$$

$$v_G = \frac{1}{\tau_G} \quad (23)$$

The above expressions are accurate and valid within the whole frequency range. If C and $G/(\omega C)$ can be regarded as frequency independent coefficients, then we obtain:

$$\tau_G = \frac{\beta}{\omega} + \frac{\beta}{2} \frac{L'}{L} + \frac{C}{4\beta} \left[-\frac{G}{\omega C} + \frac{\frac{R}{\omega L} \left(1 + \frac{G^2}{\omega^2 C^2} \right)}{\sqrt{\left(1 + \frac{R^2}{\omega^2 L^2} \right) \left(1 + \frac{G^2}{\omega^2 C^2} \right)}} \right] \left(-R + R' \omega - \frac{L' R}{L} \omega \right) \quad (24)$$

The above expressions, which are valid within the entire frequency range, can be simplified into approximate expressions, which are valid at high or low frequencies only.

4.3 High frequency representation of secondary parameters

The high frequency representations of the formulas are useful over a broad range of frequencies extending from voice frequency on up because of the range of values for the dissipation factor. $G/(\omega C) = \tan \delta < 0,03$ ($< 3\%$) even for PVC insulated cables up to 1,5 MHz and for the polyethylene (PE), insulation is very small at about 0,000 1 (0,01 %). This results in approximations, which in practice are valid for the whole frequency range as follows:

$$Re Z_C \approx \sqrt{\frac{L}{C}} \sqrt{\frac{1}{2} + \frac{1}{2} \sqrt{1 + \frac{R^2}{\omega^2 L^2}}} \quad (25)$$

$$-Im Z_C \approx \frac{R}{2\omega C Re Z_C} - \frac{G}{\omega C} Re Z_C + \frac{\frac{G}{2\omega C} \frac{L}{C}}{Re Z_C} \quad (26)$$

$$\alpha \approx \frac{R}{2 Re Z_C} + \frac{G \left(\sqrt{\frac{L}{C}} \right)^2}{2 Re Z_C} \quad (27)$$

$$\beta \approx \omega C Re Z_C \quad (28)$$

$$\tau_P \approx \sqrt{LC} \quad (29)$$

$$\tau_G \approx \frac{\beta}{\omega} + \frac{\beta}{2} \frac{L'}{L} + \frac{C}{4\beta} \left[-\frac{G}{\omega C} + \frac{\frac{R}{\omega L}}{\sqrt{1 + \frac{R^2}{\omega^2 L^2}}} \right] \left(-R + R' \omega - \frac{L' R}{L} \omega \right) \quad (30)$$

when also $R/(\omega L) < 0,1$, which is true for high frequencies ($f > 1$ MHz for 0,5 mm wire), the formulas holding better than about 1 % accuracy can be further simplified as shown below.

$$Re Z_C \approx \sqrt{\frac{L}{C}} \quad (31)$$

$$-Im Z_C \approx \frac{R}{2\omega C Re Z_C} - \frac{G}{\omega C} Re Z_C \approx \sqrt{\frac{L}{C}} \left(\frac{R}{2\omega L} - \frac{G}{2\omega C} \right) \quad (32)$$

$$\alpha \approx \frac{R}{2 Re Z_C} + \frac{G}{2} Re Z_C \approx \frac{R}{2} \sqrt{\frac{C}{L}} + \frac{G}{2} \sqrt{\frac{L}{C}} \quad (33)$$

$$\beta \approx \omega C Re Z_C \approx \omega \sqrt{LC} \quad (34)$$

$$\tau_P \approx \sqrt{LC} \quad (35)$$

$$\tau_G \approx \tau_P + \frac{\beta}{2} \frac{L'}{L} + \frac{C}{4\beta} \left(-\frac{G}{\omega C} + \frac{R}{\omega L} \right) \left(-R + R' \omega - \frac{L' R}{L} \omega \right) \quad (36)$$

4.4 Frequency dependence of the primary and secondary parameters

4.4.1 Resistance

The high frequency resistance (surface resistance) of a solid round wire for frequencies where the wire radius r is greater than twice the skin depth δ can be regarded as consisting of two parts where one is constant and the other $f^{0,5}$ dependent.

$$R = R_C + R_S = R_C + \rho \sqrt{\omega} \approx R_0 \left(\frac{1}{4} + \frac{r}{2\delta} \right) \quad (37)$$

$$\rho = \frac{R_S}{\sqrt{\omega}} = \frac{R_0 r}{4} \sqrt{2\mu\sigma} \quad (38)$$

The above is true for a solid wire alone. In a pair, the proximity effects and the presence of other pairs and possible screen contribute both to the resistance and inductance. These effects can increase the R by about 15 % at 1 MHz and follow also approximately the square-root of frequency law. Also, the constant component of resistance while often neglected, is about 15 % of the frequency dependent component at 1 MHz for a 0,5 mm diameter copper pair.

4.4.2 Inductance

The total inductance consists also of two main components such that

$$L \approx L_E + L_I = L_E + \frac{R_S}{\omega} = L_E + \frac{\rho}{\sqrt{\omega}} \quad (39)$$

The external free space inductance is reduced by the proximity effect of the pair and the free space limiting effects of the nearby shield and/or other pairs. These inductive components are negative and fairly frequency independent at high frequencies.

4.4.3 Characteristic impedance

The characteristic impedance high frequency asymptotic value Z_{∞} is given by Equation (40).

$$Z_{\infty} = \sqrt{\frac{L_E}{C}} \quad (40)$$

The high frequency impedance formulas are given by Equations (41) and (42):

$$Re Z_C \approx \sqrt{\frac{L}{C}} \approx Z_{\infty} \left(1 + \frac{R_S}{2 \omega L_E} \right) = Z_{\infty} + \frac{\rho}{2 \sqrt{L_E C} \sqrt{\omega}} \quad (41)$$

$$\begin{aligned} -Im Z_C &\approx \sqrt{\frac{L}{C}} \left(\frac{R}{2 \omega L} - \frac{G}{2 \omega C} \right) \\ &\approx \frac{R_C + \rho \sqrt{\omega}}{2 \omega \sqrt{L_E C} \left(1 + \frac{\rho}{2 L_E \sqrt{\omega}} \right)} - \sqrt{\frac{L_E}{C}} \left(1 + \frac{\rho}{2 L_E \sqrt{\omega}} \right) \frac{\tan \delta}{2} \\ &\approx \frac{R_C}{2 \omega \sqrt{L_E C}} + \frac{\rho}{2 \sqrt{L_E C} \sqrt{\omega}} - \frac{Z_{\infty}}{2} \left(1 + \frac{L_l}{L_E} \right) \tan \delta \\ &\approx \frac{\rho}{2 \sqrt{L_E C} \sqrt{\omega}} - \frac{Z_{\infty}}{2} \tan \delta \end{aligned} \quad (42)$$

4.4.4 Attenuation coefficient

Using the above approximations with Equations (31) through (36) results in the remaining equations of this subclause:

$$\alpha \approx \frac{\left(R_C - \frac{\rho^2}{2 L_E} \right)}{2 Z_{\infty}} + \frac{\rho \sqrt{\omega}}{2 Z_{\infty}} + \frac{\rho \sqrt{\omega} \tan \delta}{4 Z_{\infty}} + \frac{\omega \sqrt{L_E C} \tan \delta}{2} \quad (43)$$

which is of the form:

$$\alpha \approx A + B \sqrt{\omega} + C \omega \quad (44)$$

where A , B and C are constants.

The first term of Equation (44) indicates that at the low end of the high frequency range the attenuation increases a little more slowly than the square-root-law. The first $\omega^{0.5}$ term in Equation (43) which is dominant in the high frequency attenuation formula also appears in the phase coefficient, Equation (45).

$$\beta \approx \omega \sqrt{LC} \approx \omega \sqrt{L_E C} \left(1 + \frac{R}{2 \omega L_E} \right) \approx \omega \sqrt{L_E C} + \frac{\rho \sqrt{\omega}}{2 Z_{\infty}} \quad (45)$$

4.4.5 Phase delay and group delay

The phase and group delay are given in Equations (46) and (47) respectively:

$$\tau_P \approx \sqrt{LC} = \sqrt{L_E C} \left(1 + \frac{R}{2\omega L_E} \right) \approx \sqrt{L_E C} + \frac{\rho}{2Z_\infty \sqrt{\omega}} \quad (46)$$

$$\begin{aligned} \tau_G &\approx \tau_P + \frac{\beta}{2} \frac{L'}{L} + \frac{C}{4\beta} \left(-\frac{G}{\omega C} + \frac{R}{\omega L} \right) \left(-R + R' \omega - \frac{L' R}{L} \omega \right) \\ &\approx \left(1 - \frac{R}{4\omega L} \right) - \frac{R}{8\omega L} \left(\frac{R}{\omega L} - \frac{G}{\omega C} \right) \\ &\approx \tau_P \left(1 - \frac{R}{4\omega L} \right) \\ &\approx \sqrt{L_E C} \left(1 + \frac{R}{4\omega L_E} \right) \\ &\approx \sqrt{L_E C} + \frac{\rho}{4\sqrt{\omega} Z_\infty} \end{aligned} \quad (47)$$

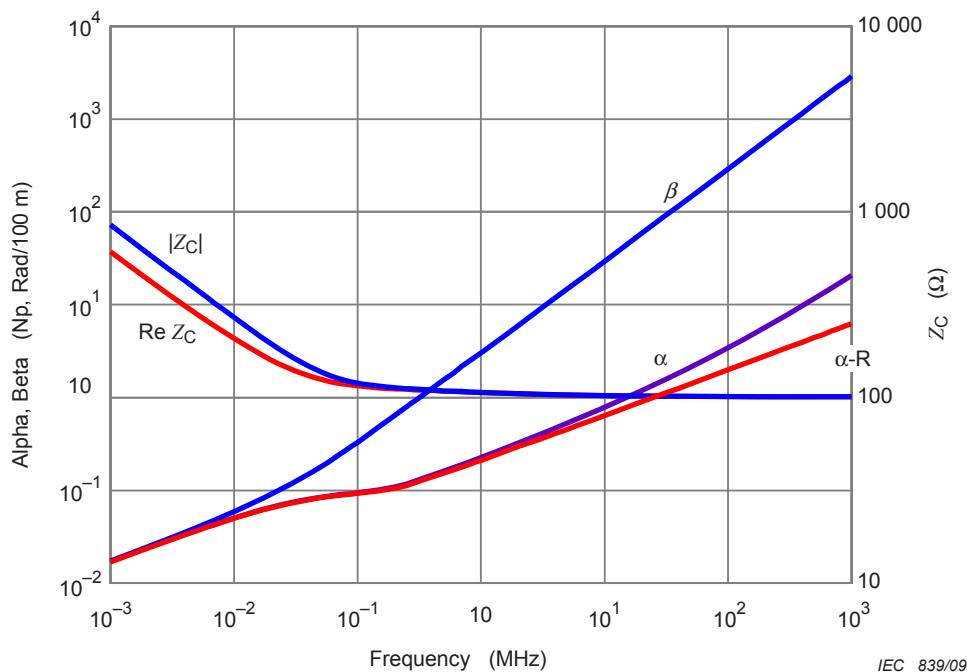


Figure 1 – Secondary parameters extending from 1 kHz to 1 GHz

Figure 1 shows the secondary parameters of a UTP pair with 0,5 mm conductors versus frequency. At voice frequencies, the attenuation and phase coefficients are substantially equal. At these frequencies, the absolute value of the characteristic impedance and the real part of the characteristic impedance differ by the square-root of 2. At frequencies above 100 kHz, attenuation is much less than the phase coefficient on the Nepers and radians scale, and the characteristic impedance is mostly real. The total attenuation (Alpha) differs from the conductor attenuation (Alpha-R) by the dielectric component of attenuation for this example, where the dissipation factor is assumed to be 0,01.

5 Measurement of characteristic impedance

5.1 General

The characteristic impedance Z_C of a homogeneous cable pair is defined as the quotient of a voltage wave and current wave which are propagating in the same direction, either forwards (f) or backwards (r). For homogeneous cables (with no structural variations), the characteristic impedance can be measured directly as the quotient of voltage U and current I at the cable ends.

$$Z_C = \frac{U_f}{I_f} = \frac{U_r}{I_r} \quad (48)$$

A number of methods for obtaining characteristic impedance are described. Some of these methods offer convenience (perhaps at the cost of accuracy in portions of the frequency range). Others offer capability beyond what is currently needed for routine product inspection but are useful in laboratory evaluation where measurement throughput is not as critical.

The open/short circuit single-ended impedance measurement made with a balun in 5.2 is viewed as the reference method for obtaining the data. Alternative methods are listed below:

- a) characteristic impedance determined from phase coefficient and capacitance measurements (see 5.4);
- b) terminated cable impedance measurements (see 5.5);
- c) extended open/short impedance measurements excluding balun performance (see 5.6);
- d) extended open/short impedance measurements made without a balun (see 5.7);
- e) open/short impedance measurements at low frequencies with a balun (see 5.8);
- f) impedance measurements obtained by modal decomposition technique (see 5.9).

It is intended that impedance measurements will be performed using sufficiently closely spaced frequencies so that impedance variation is adequately represented. Either a linear sweep or a logarithmic sweep may be used depending on whether the high end or low end, respectively, of the desired frequency range is to be more fully represented. Typically, several hundred points (such as the available 401 points) are required depending on frequency range and cable length.

The balun used for connecting the symmetric cable pair to the coaxial port on the test instrument shall have a pass-band frequency range adequate for the desired measurement range. It shall be capable of transforming from the instrument port impedance to the nominal pair impedance. The three step impedance measurement calibration is performed at the secondary (pair side) of the balun.

Function fitting (discussed in 5.3) of the impedance data is useful for separating structural effects from the characteristic impedance when such effects are substantial. Where function fitting is used, the concept is that measurements from nearby frequencies aid in the interpretation of the values obtained at a particular frequency. Function fitting of the impedance magnitude or real part results in high values (typically 0,5 Ω or less) because of the positive and negative deviations not being symmetrical on the impedance scale. Function fitting can be carried out on the S -parameter values, which are linear responses, if more rigorous results (both impedance and SRL) are desired.

5.2 Open/short circuit single-ended impedance measurement made with a balun (reference method)

5.2.1 Principle

Open and short circuit measurements made with a balun from one end of a symmetric cable pair is the reference method for obtaining characteristic impedance values. The characteristic impedance is the geometric mean of the product of the open and short circuit measured values and is defined as:

$$Z_C = \sqrt{Z_{OC} Z_{SC}} \quad (49)$$

When the cable is not homogenous, an impedance inclusive of structural effects is obtained:

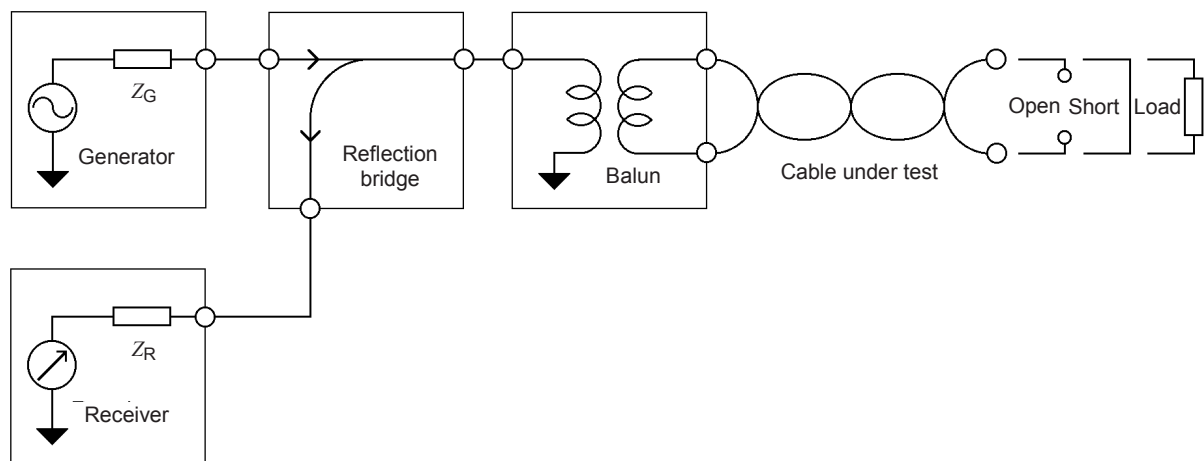
$$Z_{CM} = \sqrt{Z_{OC} Z_{SC}} \quad (50)$$

where Z_{CM} is the complex characteristic impedance together with structure (input impedance), expressed in ohms (Ω).

Equation (49) represents the characteristic impedance, Z_C , when structural effects are negligible. The fitting of the open/short impedance data with a characteristic impedance such as function of frequency can be employed to obtain Z_C from the input impedance, Z_{CM} , Equation (50) when structural effects are substantial. Equations (49) and (50) (and this measurement technique) are valid for frequencies extending from low values, where the cable length is only a fraction of a wavelength, to high frequencies where cable length represents many wavelengths.

5.2.2 Test equipment

A network analyser (together with an S -parameter unit) or an impedance meter can be used to obtain the data. Figure 2 shows the main components of an impedance measurement circuit where the generator and receiver are parts of the network analyser. An S -parameter unit, where the key component is the reflection bridge, is used with a network analyser to separate the reflected signal from the incident signal. A balun with the appropriate frequency range, impedance (such as 50 Ω to 100 Ω for 50 Ω equipment and 100 Ω pair) and balanced at least as well as the pair under test facilitates making measurements on symmetric pairs under balanced conditions. Three terminating conditions, open, short and the nominal load resistance, are used as appropriate for the type of measurement being made (open, short or terminated).



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Figure 2 – Diagram of cable pair measurement circuit

5.2.3 Procedure

A three step calibration procedure using the same open, short and load terminations as used for the actual measurements is carried out at the secondary of the balun with the cable pair disconnected. Upon completing the 3-step calibration procedure at the secondary of the balun, the network analyser is capable of measuring directly the complex reflection coefficient (S -parameter) or impedance of a cable pair. An internal 3-step calibration procedure including calculations is provided by most network analysers when an S -parameter unit is used. The method presented in 5.6 covers a similar 3-step calibration procedure by using the F-matrix principle where all the quantities are stated as impedances. This method is useful when the network analyser is not suitably equipped, in which case the computations can be accomplished external to the analyser.

The measured impedance (open or short) is computed from the reflection coefficient measurements S_{11} by means of Equation (51) either by the network analyser or by a computer (on acquired data):

$$Z_{\text{MEAS}} = Z_R \frac{1 + S_{11}}{1 - S_{11}} \quad (51)$$

5.2.4 Expression of results

Conceptually, several approaches are possible. On the one hand, the input impedance consisting of the combined characteristic impedance and structural effects can be viewed as needing to meet a broader single requirement (such as the 85 Ω to 115 Ω range) over the specified frequency range. Alternatively, a narrower range (such as a 95 Ω to 105 Ω range) can be viewed as being a requirement for the asymptotic component of function fitted characteristic impedance. In this case, RL or SRL specifications are used to control structural effects. The advantage of a broad single requirement in many instances is measurement simplification.

The advantage of separating the two effects is that of obtaining quantitative information for the two effects. The requirements for the impedance and structural effects are given in the relevant cable specification.

5.3 Function fitting the impedance magnitude and angle

5.3.1 General

Function fitting of the impedance data is useful for separating structural effects from the characteristic impedance when such effects are substantial. Where function fitting is used, the concept is that measurements from nearby frequencies aid in the interpretation of the values obtained at a particular frequency. Function fitting of the impedance magnitude or real part results in high values (typically 0,5 Ω or less), because of the positive and negative deviations not being symmetrical on the impedance scale. Function fitting can be carried out on the *S*-parameter values, which are linear responses, if more rigorous results (both impedance and *SRL*) are desired.

5.3.2 Impedance magnitude

5.3.2.1 Function fitting the magnitude of the characteristic impedance

While function fitting can be applied to the real and imaginary components of Z_C , the usual situation is that interest in the magnitude is greater than interest in the two separate components or the angle. The impedance magnitude tracks the real component closely at high frequencies where the imaginary component is small.

Function fitting of the impedance magnitude or real part results in fairly high values (typically 0,5 Ω or less), because of the positive and negative deviations not being symmetric on the impedance scale. Function fitting can be carried out on the *S*-parameter values, which is a linear response scale, if more rigorous results (both impedance and *SRL*) are desired.

This method differs from smoothing in that a characteristic impedance like function (based on transmission theory) is used to fit the measured data (obtained from Equation (50) or terminated impedance data). The function is stated as follows.

The fitted characteristic impedance magnitude is calculated with a least squares curve fit to Z_C , based on Equation (52):

$$|Z_C| = K_0 + \frac{K_1}{f^{1/2}} + \frac{K_2}{f} + \frac{K_3}{f^{3/2}} \quad (52)$$

NOTE Where terminated cable impedance data is used instead of open/short data, round-trip loss of measured length should be sufficiently large (in the 10 dB to 20 dB range for desired accuracies in the 5 Ω to 1,5 Ω range respectively when maximum deviation is 15 Ω – see 5.5).

Discreet point data equally spaced according to the log of frequency is advantageous for function fitting in that it results in appropriate weighting of the lower and upper ends of a multi-decade frequency sweep. Linear frequency spacing with logarithmic weighting may be used in the calculations when log of frequency spacing leads to concern about undersampling at high frequencies. Plotting the data versus the log of frequency is helpful here (as it is in network theory). The function fitting for individual data sets can readily be accomplished by importing ASCII format data obtained from the network analyser directly into a spreadsheet program and using the built-in regression procedures. Optimized software for analyzing numerous data sets is desirable for use in a production setting.

The terms of the right hand side of Equation (52) generally diminish in importance from left to right. The first two terms have strong theoretical basis. The constant term has the strongest basis in that it represents the space (external) inductance (largest component of inductance) and the capacitance of the pair (see Clause 4). The second term is significant in that it represents the component of characteristic impedance resulting from the internal inductance. The last two terms are supplied to provide for second order effects such as the capacitance decreasing with frequency, as with polar insulation materials or the effects of a shield. In the latter case, the low frequency end function fitting range is limited to frequencies where slope is increasing with frequency (2nd derivative positive).