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TEST METHODS FOR SCREENING AND BALANCE OF COMMUNICATION CABLES

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Abstract: With the new triaxial test method all parameters, describing the screening effectiveness of balanced and unbalanced cables, can be measured in one test set-up.

1. Introduction

The frequency range of symmetrical transmission lines - i.e. balanced pairs or quads – has increased up to the GHz range. Especially in the field of data transmission, e.g. in applications of horizontal floor wiring for data communication, a high screening effectiveness respectively a good electromagnetic compatibility (EMC) is required.

In order to measure the screening effectiveness of those cables, new measuring procedures have been developed. The new procedures are now under discussion in the European and international standardisation [1,2,3,4,5,6,7,8,9,17,18,19].

For balanced cables the EMC is described by the coupling attenuation a_c. The coupling attenuation a_c covers both effects, the screening attenuation of the screen and the unbalance of the transmission line. The screening effectiveness of cable screens is described by the surface transfer impedance Z_T in the lower frequency range and the screening attenuation a_s in the upper frequency range. The symmetry is described by the unbalance attenuation of the balanced transmission line.

With the new triaxial measuring procedure all of those parts of the screening effectiveness – surface transfer impedance, screening attenuation, unbalance attenuation and coupling attenuation – can be measured with one test set-up. The unbalance attenuation is measured as the difference between coupling attenuation and screening attenuation. In this way it is possible to measure the unbalance attenuation up to the GHz frequency range with baluns, having no centre tap.

2. Physical basics

2.1 General coupling equations

It is expedient to use the concept of operational attenuation with the square root of power waves, like in the definition of scattering parameters [3,10]. The general coupling transfer function is then defined as:

$$T_{\substack{n\\f}} = \frac{\underline{U}_{\substack{2n\\f}} \Big/ \sqrt{Z_2}}{\underline{U}_1 \Big/ \sqrt{Z_1}} = \frac{\sqrt{\underline{P}_{\substack{2n\\f}}}}{\sqrt{\underline{P}_0}} \qquad (1)$$

The electromagnetic influence between the cable and the surrounding is in principle the crosstalk between two lines

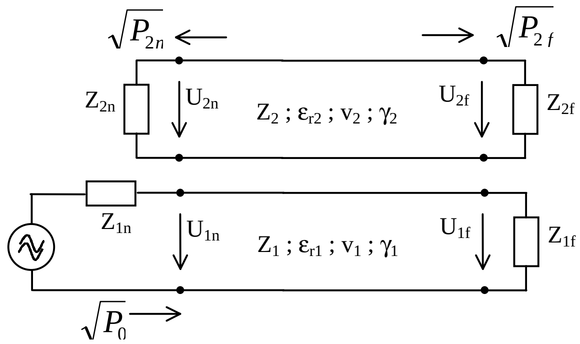


Fig. 0: Equivalent circuit for general coupling transfer function

and is caused by capacitive and magnetic coupling. At the near end the magnetic and capacitive coupling add where at the far end they subtract [10,11,12,13,14]. The coupling over the whole cable length is obtained by integrating the infinitesimal coupling distribution along the cable with the correct phase. The phase effect, when summing up the infinitesimal couplings along the line is expressed by the summing function S [3,11]. When the cable attenuation is neglected S could be expressed by the following equation.

$$S_{\substack{n\\f}}(lf) = \frac{\sin(\beta_2 \pm \beta_1)\cdot l/2}{(\beta_2 \pm \beta_1)\cdot l/2} \exp(-j(\beta_2 + \beta_1)\cdot l/2) \qquad (2)$$

For high frequencies the asymptotic value becomes:

$$\left| S_{\substack{n\\f}} \right| \rightarrow \frac{2}{(\beta_1 \pm \beta_2)\cdot l} \qquad (3)$$

And for low frequencies the summing function becomes:

$$\left| S_{\substack{n\\f}} \right| \rightarrow 1 \qquad (4)$$

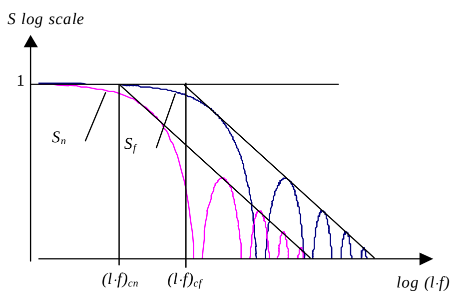


Fig.1: Summing function S

The point of intersection between the asymptotic values for low and high frequencies is the so called cut-off frequency f_c. This frequency gives the condition for electrical long cables:

$$f_{c,\frac{n}{f}} \cdot l \ge \frac{c}{\pi \cdot \left|\sqrt{\varepsilon_{r1}} \pm \sqrt{\varepsilon_{r2}}\right|} \tag{5}$$

2.2 Screen related parameter

In [3,11,13] the coupling through the screen is described in detail. The following gives a short summary of the literature.

2.2.1 Surface transfer impedance

In many cases, above all in the lower frequency range, the screening effectiveness of cable screens is described by the transfer impedance Z_T. It is, for an electrically short peace of cable, defined as the quotient of the longitudinal voltage measured on the secondary side of the screen to the current in the screen, caused by a primary inducing circuit, related to unit length [15]. Although the transfer impedance Z_T covers only the galvanic and magnetic couplings it is common practice to use it as a quantity as well, which includes the effect of the coupling capacitance C_T through the cable screen [11]. In this case it is named equivalent transfer impedance Z_{TE}, including the effects of galvanic, magnetic and capacitive coupling.

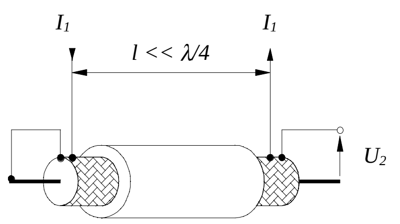


Fig. 2: Definition of transfer impedance

$$Z_T = \frac{U_2}{I_1 \cdot l} \tag{6}$$

2.2.2 Coupling admittance, capacitive coupling impedance

For the determination of the proper coupling capacitance there is, as standardised quantity, the capacitance coupling admittance Y_T. The coupling admittance, for an electrically short peace of cable, is defined as the quotient of the current in the screen caused by the capacitive coupling in the secondary circuit to the voltage in the primary circuit related to unit length [15].

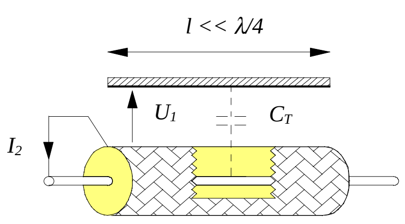


Fig. 3: Definition of coupling admittance

$$Y_T = \frac{I_2}{U_1 \cdot l} = j\omega \cdot C_T \tag{7}$$

The through capacitance C_T and thus the capacitive coupling admittance Y_T are dependent on the permittivity and geometry of the outer circuit. In order to have a quantity which is invariant on the permittivity and geometry of the outer circuit and is also comparable to the transfer impedance Z_T the capacitive coupling impedance Z_F is introduced [3,8,11]

$$Z_F = Z_1 \cdot Z_2 \cdot Y_T \tag{8}$$

2.2.3 Coupling Transfer Function

The transfer impedance Z_T and the capacitive coupling impedance Z_F of homogeneous screens are constant along the cable length. The integration along the cable could then be easily solved. For matched lines the coupling transfer function is then expressed by [3,11]:

$$T_{s,\frac{n}{f}} = \left(Z_F \pm Z_T\right) \cdot \frac{1}{\sqrt{Z_1 \cdot Z_2}} \cdot \frac{l}{2} \cdot S_{\frac{n}{f}} \tag{9}$$

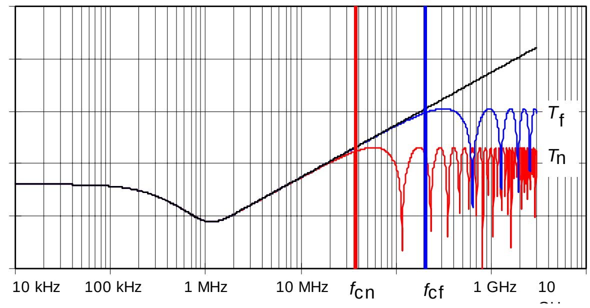


Fig. 4: calculated coupling transfer function (l = 1 m; ε_{r1} = 2,3; ε_{r2} = 1; Z_F=0)

Fig. 4 shows the effect of the summing function S. If the cable becomes electrical long (eq. 5) then the coupling transfer function starts to oscillate with a constant envelope.

2.2.4 Screening attenuation

The screening attenuation is defined as the logarithmic ratio of the power fed into the matched cable and the maximum peak power in the matched outer circuit, in a frequency range where the cable is electrical long [8,15]. From Fig. 4 we observe, that the maximum peak power for electrical long cables is constant over the frequency.

$$a_s = 10\log_{10}\left|\frac{P_1}{P_{2,\max}}\right| = 20\log_{10}\left[\max\left\{Env(T_n); Env(T_f)\right\}\right] \tag{10}$$

2.3 Unbalance attenuation

Screened balanced pairs may be operated in the differential mode (balanced) or the common mode (unbalanced). In the differential mode one conductor carries the current $+I$ and the other conductor carries the current $-I$; the screen is without current. In the common mode both conductors of the pair carry half of the current $+I/2$; and the screen is the return path with the current $-I$, comparable to a coaxial cable.

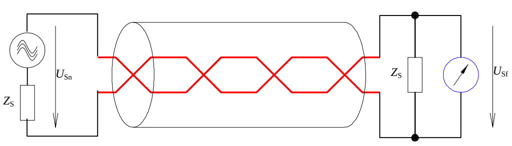


Fig. 5a: Differential mode of a screened pair (STP)

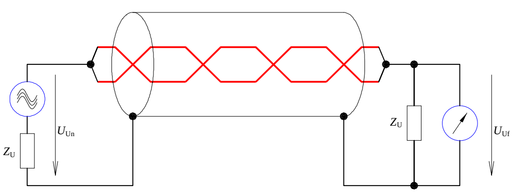


Fig. 5b: Common mode of a screened pair (STP)

Under ideal conditions respectively with ideal cables both modes are independent of one another. Actually both modes influence each other. Differences in the diameter of the core insulation, unequal twisting and different distances of the cores to the screen are some reasons for the unbalance of the pair. The unsymmetry is caused by the capacitive unbalance to earth **e** (cross-unsymmetry) and the difference of the inductance and resistance between the two wires **r** (longitudinal-unsymmetry) [12,14,16,22].

$$e = C_{10} - C_{20} \tag{11}$$

$$r = \left(R_2 + j\omega L\right)_2 - \left(R_1 + j\omega L_1\right) \tag{12}$$

The coupling between the two lines is then expressed by:

$$T_{u,n} = \frac{1}{4} \cdot \frac{1}{\sqrt{Z_{diff} Z_{com}}} j\omega \int_0^l \left[e(x) Z_{diff} Z_{com} + \frac{r(x)}{j\omega} \right] \cdot e^{-\left(\gamma_{diff} + \gamma_{com}\right) x} dx \tag{13}$$

$$T_{u,f} = \frac{1}{4} \cdot \frac{1}{\sqrt{Z_{diff} Z_{com}}} j\omega \int_0^l \left[e(x) Z_{diff} Z_{com} - \frac{r(x)}{j\omega} \right] \cdot e^{\left(\gamma_{diff} - \gamma_{com}\right)(l-x)} dx \tag{14}$$

Where Z_{diff} is the characteristic impedance of the differential mode (balanced) and Z_{com} of the common mode (unbalanced). These are in principle the same coupling transfer functions compared to the coupling through the screen. The integral could only be solved if the distribution of the unsymmetry along the cable length is known. For an unsymmetry being constant along the cable length, the transfer function results in the same way as for cable screens (see 2.2.3)

$$T_{u,\frac{n}{f}} = j\omega\left(eZ_{diff} Z_{com} \pm r\right) \cdot \frac{1}{\sqrt{Z_{diff} \cdot Z_{com}}} \cdot \frac{l}{4} \cdot S_{\frac{n}{f}} \tag{15}$$

If then the cable is electrical long we the have the same phenomenon as for the coupling through the screen. Depending on the velocity difference between the differential and common mode circuit the envelope of the transfer function approaches a constant value which is frequency and length independent. However if the velocity difference is zero, then the transfer function at the far end increase by 20 dB per decade over the whole frequency range (S_f =1). In praxis we have small systematic couplings together with statistical couplings. Thus $T_{u,n}$ increase by approx. 10 dB per decade and $T_{u,f}$ by less then 20 dB per decade [14].

The unbalance attenuation is defined as the logarithmic ratio of the power which couples from one mode into the other mode, related to the feeding power.

$$a_{u,\frac{n}{f}} = 20 \log_{10} \left| T_{\frac{n}{f}} \right| \tag{16}$$

The measurement of the unbalance attenuation up to the 100 MHz range is under discussion in the international standardisation [17,18,19]. Fig. 6 illustrates the principle set-up for the measurement of the unbalance attenuation.

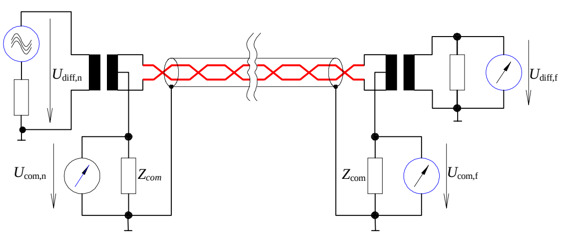


Fig. 6: Measuring set-up for unbalance attenuation

Fig. 7 shows the measuring results of the Twinax 105 Ω cable with PE insulation and PE intersheath and thus a velocity difference of nearly zero.

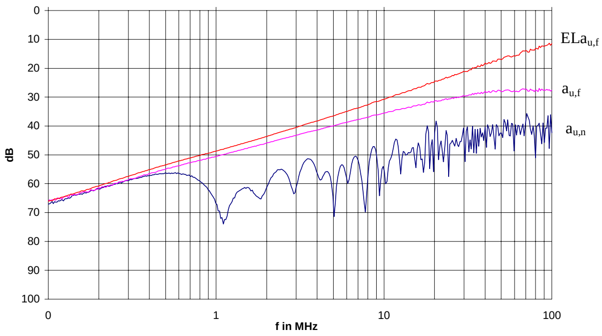


Fig. 7: Unbalance attenuation of Twinax 105 Ohm

$a_{u,n}$	Unbalance attenuation at near end
$a_{u,f}$	Unbalance attenuation at far end, including cable attenuation
$Ela_{u,f}$	Equal level unbalance attenuation at far end, excluding cable attenuation

2.4 Coupling attenuation

As discussed above, balanced cables which are driven in the differential mode will, due to irregularities in the cable symmetry, radiate a part of the input power.

For unscreened balanced cables (UTP) this radiation is depicted by the unbalance attenuation a_U.

For screened balanced cables (STP), the disturbing power from the pair is additional attenuated by the outer screen. The unbalance causes a current in the screen which is then coupled by the transfer impedance and capacitive coupling impedance into the outer circuit. Consequently the total effectiveness against electromagnetic disturbances of shielded balanced cable (STP) is the sum of the unbalance attenuation a_U of the pair and the screening attenuation a_S of the screen. Since both quantities usually are given in a logarithmic ratio, they may simply be added into the coupling attenuation a_C.

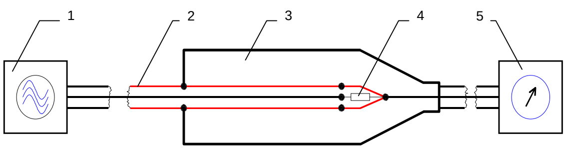
$$a_c = a_u + a_s \tag{17}$$

3. Triaxial test set-up

With the triaxial set-up the surface transfer impedance Z_T, the screening attenuation a_S, the coupling attenuation a_C and the unbalance attenuation a_U can be measured.

3.1 Principle of the triaxial set-up

On the basis of the known reversibility of primary and secondary measuring circuits, the new measuring set-up, presented in Fig. 6, actually meets the IEC 61196-1, despite the interchange of generator and receiver. The benefits of feeding the inner system, which is terminated by its characteristic impedance, are the matching of the generator and reflection free wave propagation over the cable length.



1 generator	4 termination load
2 cable under test	5 measuring receiver
3 measuring tube	l coupling length

Fig. 8: principle triaxial set-up

The triaxial test set-up consists of a tube of brass or aluminium with an inner diameter of about 40 mm. The length is 0,5 m to 1 m, when measuring the transfer impedance, and 2 m to 4 m or more when measuring the screening attenuation or the coupling attenuation.

The total length of 2 m or more may be achieved by screwing single parts of tubes (RF-tight) together.
At the near end the screen under test is short circuited with the measuring tube. The electrical waves which are coupled from the inner system into the outer system over the whole cable length are travelling in both directions. At the short circuited end they are totally reflected, so that at the measuring receiver the superposition of near- and far end coupling can be measured as the disturbance voltage ratio U_{2f}/U_{1n} (18)

The maximum frequency which can be measured in the triaxial set-up result from the definition of the wave propagation of transversal electromagnetic waves (TEM-waves) and is given by:

$$f_g = \frac{2 \cdot c_0}{\pi \cdot \sqrt{\varepsilon_{r2}} \cdot (D_2 + d_1)} \qquad (19)$$

where d_1 is the outer diameter of the braid of the cable, D_2 is the inner diameter of the measuring tube and ε_{r2} is the resulting dielectric permittivity of the outer system. With an inner diameter of 40 mm of the tube and an outer diameter of about 3,5 mm of the braid, the maximum frequency of the system is about 4,2 GHz.

3.2 Advantages of the triaxial set-up

Due to the closed measuring fixture attenuation values up to 125 dB respectively transfer impedance's in the μ-Ohm range can be measured without additional amplifiers. The advantages are in detail:

- insensitive against electromagnetic disturbances from outside
- no radiation of electromagnetic power
- high dynamic range > 125 dB
- high reproducibility
- simple measuring set-up
- fast preparation of the cable sample
- measurement of screening attenuation a_S and transfer impedance Z_T in one go with one test fixture.

3.3 Measurement of the transfer impedance

The measurement of the transfer impedance of an electrical short peace of cable is done according to IEC 61196-1 despite of the interchange of generator and receiver (see Fig. 6). The maximum frequency up to which the transfer impedance is measured in the triaxial set-up is given by:

$$f \cdot l < \frac{c_o}{10 \cdot \sqrt{\varepsilon_{r1}}} \qquad (20)$$

3.4 Measurement of the screening attenuation

The screening attenuation of electrically long cables is measured according to IEC 46A/320/CDV. The cable is electrically long when:

$$f \cdot l \geq \frac{c}{\pi \cdot \left| \sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}} \right|} \qquad (21)$$

Due to the variable length of the tube, the frequency limit may be varied in a wide range.
A detailed description is given in [1,2,20].

3.5 Measurement of the coupling attenuation

On the basis of the absorbing clamp method [15] the measurement of the coupling attenuation with absorbing clamps has been investigated and is under study in the standardisation [6, 8]. Another method with injection clamps is described in [5, 21]. As described above the coupling attenuation is the combined result of screening attenuation and unbalance attenuation. Because the unbalance attenuation is length dependent to an uncertain amount the measurement is done on a cable length of 100 m. The absorbing clamp method has two major drawbacks, the strong influence of the outer circuit on the measuring results and reduced sensitivity caused by the high (approx. 15 dB) operational attenuation of the clamp [23]. Thus a new procedure to measure the coupling attenuation has been investigated based on the procedure to measure the screening attenuation in the triaxial set-up [7,8].
The cable under test (CUT) is centred in the tube and fed in the differential mode via a balun. The screen of the CUT is connected to the tube at the generator side. The opposite end of the cable is matched with a symmetrical/asymmetrical resistor network which matches the differential and the common mode circuit. The matching network and the connection to the screen is shielded by a screening case which forms the inner conductor of the outer system together with the screen under test.

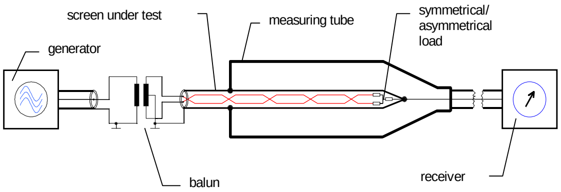


Fig. 9: Set up to measure the coupling attenuation in the triaxial set-up.

At the input end of the receiver the coupling attenuation a_c can be measured as logarithmic ratio of the differential power fed into the cable and the power in the outer circuit. The operational attenuation of the measuring leads and the balun shall be subtracted during the calibration procedure.
To measure a certain unbalance attenuation of the pair, a length of about 100 m is required. When this cable length of about 100 m is arranged between the balun and the measuring tube on the feeding side of the CUT, the sensitivity of the set up is reduced by the operational attenuation of this cable length.
To improve the sensitivity, in a further design of the set up, the required cable length of about 100 m is arranged at the receiver side of the tube. The tube at the receiver side is now open and the voltage of the second system is picked up by a feeding through connection. In this way, full sensitivity is given, only reduced by the operational attenuation of the balun and the measuring leads [9].

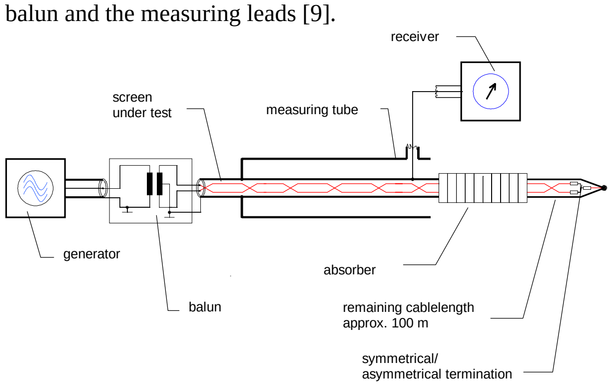


Fig. 10: Set up to measure the coupling attenuation in the modified triaxial set-up.

The ferrites at the receiver side of the tube act as a high resistance matching load, parallel to the input resistor of the receiver as well as an absorber to avoid unwanted influences.
Fig. 11 show the measured screening attenuation of the cable type RG 58 in logarithmic and linear frequency scale. One measurement has been done in the common triaxial set-up and the other in the modified triaxial set-up (open tube).

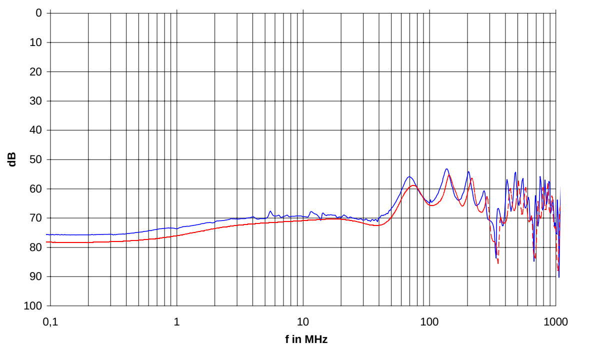


Fig. 11a: screening attenuation of RG 58 measured with the common and modified triaxial set-up; logarithmic frequency scale

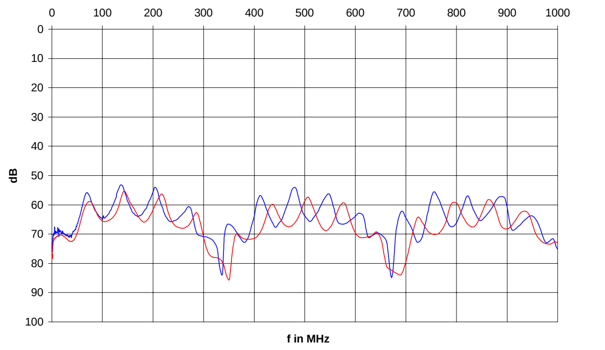


Fig. 11b: screening attenuation of RG 58 measured with the common and modified triaxial set-up; linear frequency scale

In principle we have the same results when measured with the common or the modified triaxial set-up. The difference at low frequencies in the logarithmic frequency scale is caused by the different length of the tubes. In the common triaxial set-up the coupling length has been 200 cm and in the modified triaxial set-up 207 cm. Thus we have at low frequencies the difference of approx. 2,5 dB. The difference at high frequencies in the period of the far end crosstalk is also caused by the different coupling length.

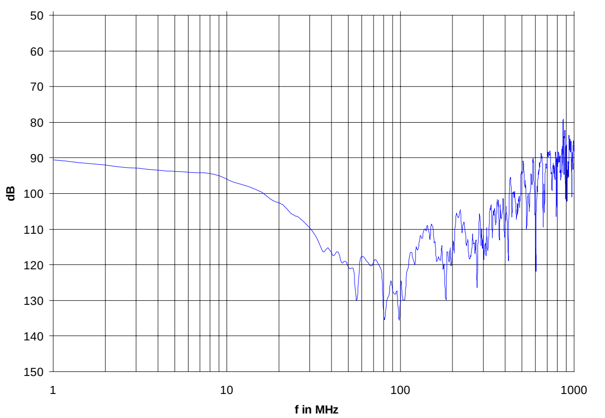


Fig. 12a: coupling attenuation of a common Cat 6 cable, coupling length 207 cm; logarithmic frequency scale.

Fig. 12 show the measuring results of the coupling attenuation in logarithmic and linear frequency scale of an shielded twisted pair cable with individual pair screen and overall screen (Cat 6).

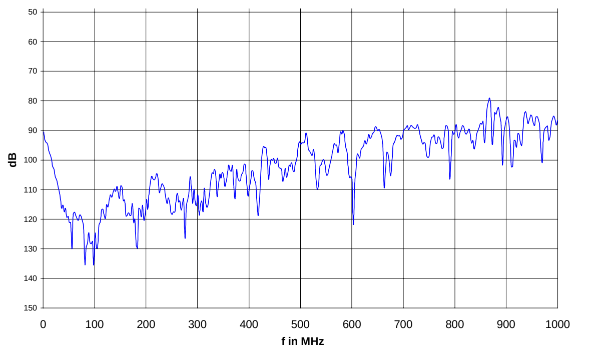


Fig. 12b coupling attenuation of a common Cat 6 cable, coupling length 207 cm; logarithmic frequency scale.

At low frequencies the attenuation is increasing due to the decreasing transfer impedance of the cable screen (longitudinal foil with a gap). At high frequencies the attenuation is decreasing due to the decreasing unbalance attenuation. The cut of frequency (eq.5) of that cable with a coupling length of 207cm is approx. 180 MHz. Behind that frequency we are talking about the coupling attenuation which is length independent.

3.6 Evaluation of the unbalance attenuation

Fig. 13 shows the measurement of the unbalance attenuation a_U with baluns according to Fig. 6, the screening attenuation a_S as well as the coupling attenuation a_C of a screened twisted pair (Twinax 105) measured in the triaxial set-up.
The curve "a_C - max(a_S)" is calculated as the difference of the coupling attenuation a_C and the max. value of the screening attenuation a_S . The envelope of the resulting curve is nearly identical to the measured unbalance attenuation a_U. (The slope down of the curves at frequencies > 250 MHz is caused by non linearities of the baluns).
By measuring the screening attenuation and the coupling attenuation, the unbalance attenuation of the pair up to high frequencies can be evaluated, with baluns having no centre tap.

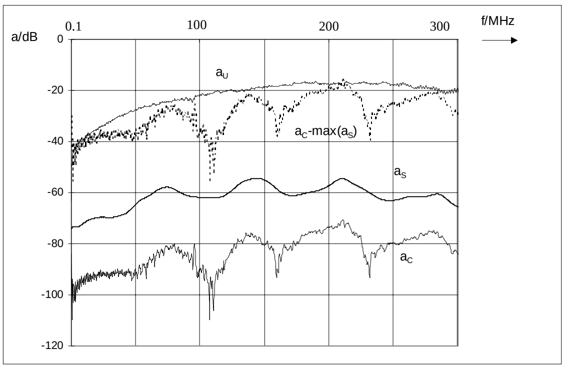


Fig. 13: Curves of unbalance, screening attenuation, coupling attenuation and calculated unbalance of a screened twisted pair (Twinax 105).

a_U:	measured unbalance attenuation (far end)
a_S:	measured screening attenuation (common mode)
a_C:	measured coupling attenuation (differential mode)
a_C-max(a_S):	calculated unbalance attenuation

4 Conclusion

Up to now, the measurement of the transfer impedance Z_T, the screening attenuation a_S and the coupling attenuation a_C required two measuring set-ups, e.g. the triaxial set-up, or the line injection set-up, and the absorbing clamp set up.
With the new triaxial measuring set-up both, the transfer impedance Z_T in the lower frequency range as well as the screening attenuation a_S in the higher frequency range up to more than 4 GHz can be measured. Furthermore the coupling attenuation and the unbalance attenuation of screened symmetrical cables can be measured.
Due to the closed measuring fixture attenuation values of more than 125 dB respectively transfer impedances in the µ-Ohm range may now be measured easily, without additional amplifiers or a shielded cabin.

5 Further investigation

Further investigations should be taken concerning the behaviour respectively the interpretation of measuring results of unscreened pairs (UTP). The measured coupling attenuation increases with increasing the diameter of the measuring tube, due to decreasing capacitance unbalance to earth. Such measuring results, (opposite to the results of screened pairs), will give no information of the EMC-behaviour of the unscreened pair under installation, e.g. on a metallic cable tray.

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Appendix A: transfer impedance, triaxial method
Appendix B: transfer impedance; line injection method
Appendix C: screening attenuation, triaxial method
Appendix D: coupling attenuation, absorbing clamp method

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