EMC – Parameter of Single Pair Ethernet Cables

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Currently, single-pair cables are already used in industrial and automotive applications. For cables used for structured cabling according to *ISO/IEC 11801* and *EN 50173*, standards are as well available and under development, *IEC 61156-11*, *-12* and *-13*. The screening performance of such balanced cable can be described as coupling attenuation, which can be understood as the interaction of balance performance of the pair and screening performance of the screen. Standardized measurement procedures for coupling attenuation for frequencies of 30 MHz and higher are *IEC 62153-4-5*, absorbing clamp method, and *IEC 62153-4-9*, triaxial method. As the main application for single pair cable run at frequencies below 30 MHz, a comparable method for the screening performance of balance cable according to *IEC 61156-11* to *-13* for frequencies below 30 MHz is needed.

Transfer impedance according to *IEC 62153-4-3* for frequencies below 30 MHz only covers the effect of the screen, not the balance performance of the pair. Therefore, an amendment to *IEC 62153-4-9* introduces the Low Frequency Coupling Attenuation (LFCA) using the same measurement setup as for coupling attenuation.

This paper that this article is based on describes LFCA in the context of the usual measurement methods for screening performance. Measurement results of a round robin test are shown and compared to calculations of advanced modelling. Furthermore, the suitability of LFCA for unscreened cables is evaluated because the mentioned standards also include options for unscreened cables and cabling.

LFCA results are well comparable between different labs, which implies good reproducibility. The proposed limit according to Type I seems to be suitable for the tested well-screened cable samples. It is obvious that low screening performance can be achieved with less effort.

For one of these designs alien crosstalk measurements have been performed and the result is achieving the limits of the already published *IEC 61156-11*. Therefore, it can be assumed that screening performance according to Type I is sufficient to fulfil alien crosstalk requirements by design. Whether also Type 1b is sufficient needs to be evaluated by further studies.

Physical Background

General coupling functions. For the measurement of coupling it is expedient to use the concept of operational attenuation with the square root of power waves, like in the definition of scattering parameters[1,2,3,21]. The general coupling transfer function is then defined as:

$$T_{\substack{n\\f}} = \frac{U_{\substack{2n\\f}}/\sqrt{Z_2}}{U_1/\sqrt{Z_1}} = \frac{\sqrt{P_{\substack{2n\\f}}}}{\sqrt{P_0}} \tag{1}$$

The electromagnetic influence between the cable and the surrounding is in principle the crosstalk between two lines and is caused by capacitive and magnetic coupling[1,2,21]. At the near end, the magnetic and capacitive coupling add where at the far end they subtract. The coupling over the whole cable length is obtained by integrating the infinitesimal coupling distribution along the cable with the correct phase (**Figure 1**).

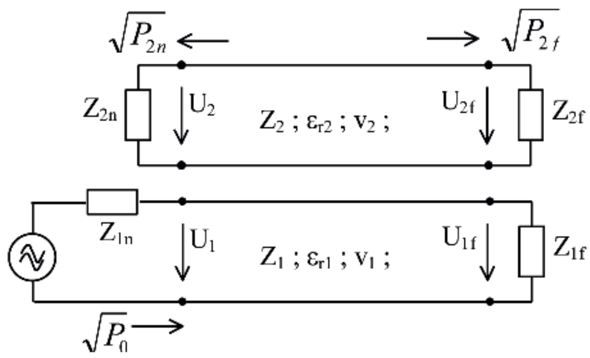

Fig. 1 — Equivalent circuit of the coupling of two lines.

The phase effect, when summing up the infinitesimal couplings along the line, is expressed by the summing function S[1,2]. When the cable attenuation is neglected the summing function S could be expressed by the following equation:

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

For high frequencies the asymptotic value becomes:

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

See **Figure** 2. And for low frequencies the summing function becomes:

$$\left|S_{\substack{n\\f}}\right| \rightarrow 1 \tag{4}$$

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

$$f_{c,\substack{n\\f}} \cdot l \geq \frac{c_0}{\pi\cdot\left|\sqrt{\varepsilon_{r1}} \pm \sqrt{\varepsilon_{r2}}\right|} \tag{5}$$

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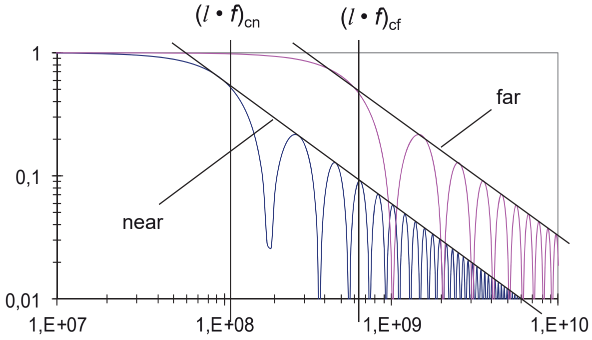
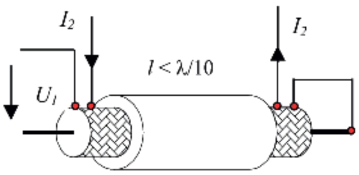


Fig. 2 — Summing function.

Screening parameter of coaxial cables. In[1, 21], the coupling through a cable shield is described in detail. The following is a brief summary of the literature.

Transfer impedance. The transfer impedance Z_T is defined as the ratio of the voltage drop U_l along the screen on the disturbed side to the interference current I_l on the other side of the screen. The dimension of the coupling resistance is milliohms per meter. According to the definition, it can be measured on electrically short test objects[21, 22]. See **Figure 3**.

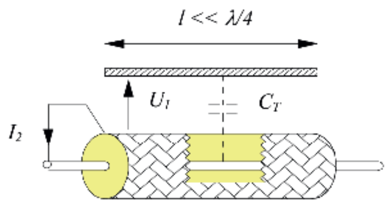


$$Z_T = \frac{U_1}{I_2 \cdot l} \tag{6}$$

Fig. 3 — Definition of transfer impedance Z_T.

Coupling admittance. For the determination of the proper coupling capacitance there is, as standardized 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[21]. See **Figure 4**.



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

Fig. 4 —Definition of capacitance coupling admittance Y_T.

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[1,2].

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

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[6, 23]. From **Figure 4** it can be seen that the maximum peak power for electrical long cables is constant over the frequency. Details of the screening attenuation measurement are described in EIC *62153-4-4*[21, 23].

$$a_s = 10\log_{10}\left|\frac{P_1}{P_{2,\max}}\right| \tag{9}$$

$$= 20\log_{10}\left[\max\{Env(T_n); Env(T_f)\}\right] \tag{10}$$

Coupling transfer function of the (coaxial) cable screen. The electromagnetic interference between the cable and the environment is basically the crosstalk between two lines and is caused by capacitive and magnetic coupling. From equation 11, it can be seen that at the near end the magnetic and capacitive coupling add up, while at the far end the magnetic and capacitive coupling subtract[1, 3, 4]. See **Figure 5**.

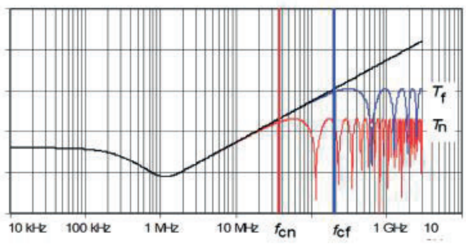


Fig. 5 — Calculated coupling transfer function, (l = 1 m; ε_{r1} = 2,3; ε_{r2} = 1; Z_F=0).

The transfer impedance Z_T and the capacitive coupling impedance Z_F of homogeneous shields are constant over the length of the cable. The integration along the cable can then easily be solved. For matched lines the coupling transfer function is then expressed by[1, 2]:

$$T_{\substack{s,n\\f}} = (Z_F \pm Z_T) \cdot \frac{1}{\sqrt{Z_1 \cdot Z_2}} \cdot \frac{l}{2} \cdot S_{\substack{n\\f}} \tag{11}$$

Figure 5 shows the effect of the sum function S. If the cable becomes electrically long (Eq. 5), the coupling transfer function begins to oscillate with a constant envelope curve.

Unbalance Attenuation of Balanced (Symmetrical) Pairs General

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 $–I$. 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[7, 8, 9]. Under ideal conditions respectively with ideal cables both modes are independent of one another. Actually both modes influence each other.

The unbalance attenuation α_U of a cable describes in a logarithmic measure how much power is coupled over from the differential mode to the common mode system (or vice versa). It is the logarithmic ratio of the power fed in the differential mode P_{diff} to the power coupled over into common-mode P_{com}.

$$a_u = 10 \cdot \log\left(P_{diff}/P_{com}\right) \qquad (12)$$

For low frequencies, the unbalance attenuation decreases with increasing length. With increasing frequency and/or length, the unbalance attenuation—similar to the shielding attenuation—asymptotically approaches a limit value (assuming systematic coupling).

The uinbalance can be determined for both the near end and the far end of a cable[5, 6, 27]. See **Figure 6**.

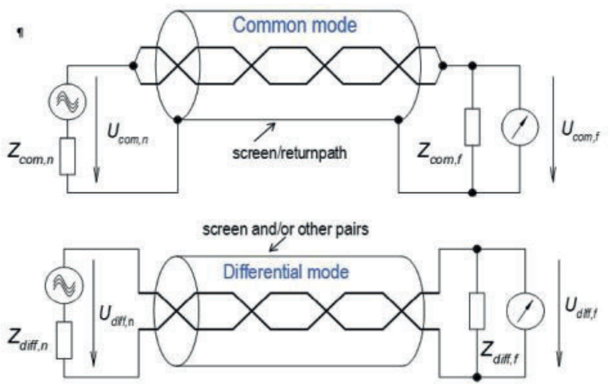


Fig. 6 — Common and differential mode of a screened twisted pair (STP).

Function of unbalance attenuation of balanced (symmetrical) pairs. 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 unbalance is caused by the capacitive unbalance to earth **e** and the difference of the inductance and resistance between the two wires **r** [3, 8, 9].

$$e = C_{10} - C_{20} \qquad (13)$$

$$\mathrm{r} = (\mathrm{R_2} + \mathrm{j\omega L_2}) - (\mathrm{R_1} + \mathrm{j\omega L_1}) \qquad (14)$$

The coupling between the two lines is then expressed by:

$$T_{u,n} = \frac{1}{4}\cdot\frac{1}{\sqrt{Z_{diff}Z_{com}}} j\omega \int_0^l \left[e(x)Z_{diff}Z_{com} + \frac{r(x)}{j\omega}\right]\cdot e^{-(\gamma_{diff}+\gamma_{com})\cdot x}dx \qquad (15)$$

$$T_{u,f} = \frac{1}{4}\cdot\frac{1}{\sqrt{Z_{diff}Z_{com}}} j\omega \int_0^l \left[e(x)Z_{diff}Z_{com} - \frac{r(x)}{j\omega}\right]\cdot e^{(\gamma_{diff}-\gamma_{com})\cdot(l-x)}dx \qquad (16)$$

Where Z_{diff} is the characteristic impedance of the differential mode (balanced) and Z_{com} of the common mode (unbalanced)[8].

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 unbalance along the cable length is known. For an unbalance being constant along the cable length, the transfer function results in the same way as for cable screens[8] to:

If then the cable is electrical long we the have the same phenomenon as for the coupling through the screen. Depending on 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

$$T_{\substack{u,n\\f}} = j\omega\left(e\cdot Z_{diff}\cdot Z_{com} \pm r\right)\cdot\frac{1}{\sqrt{Z_{diff}\cdot Z_{com}}}\cdot\frac{l}{4}\cdot S_{\substack{n\\f}} \qquad (17)$$

the whole frequency range (S_f =1). In praxis we have small systematic couplings together with statistical couplings. Thus $T_{u,n}$ increase by approximately 10 dB per decade and $T_{u,f}$ by less than 20 dB per decade[5, 8]. **Figure 7** shows the calculated unbalance of a pair with a capacitance unbalance of 1,2 pF/m and a resistance unbalance of 4,5 Ω/km[10].

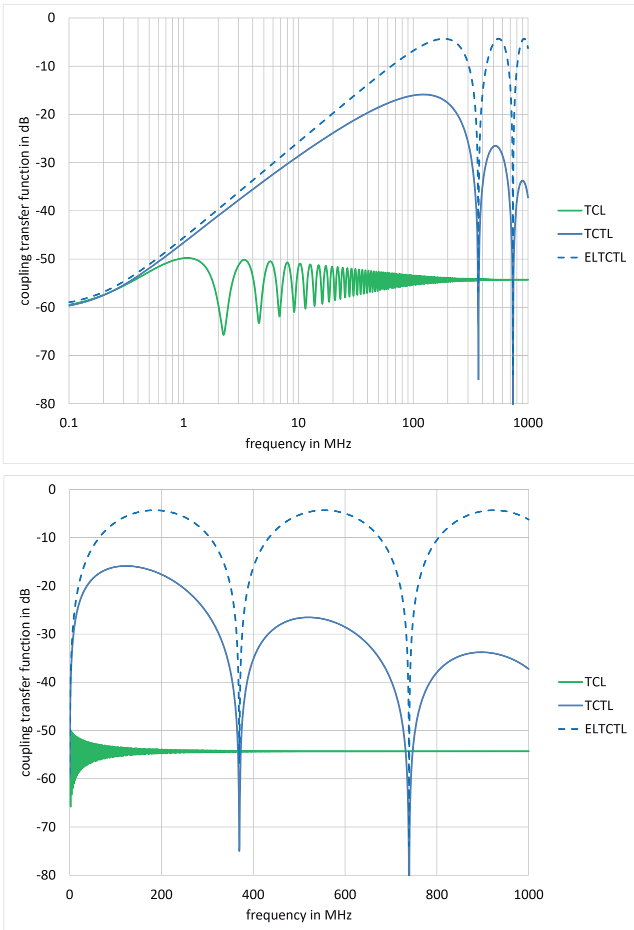


Fig. 7 — Calculated unbalance TCL, TCTL and ELTCTL of a balanced pair of 50 m, with logarithmic and linear frequency scale.

Coupling Transfer Function of Screened Balanced Pairs

The coupling attenuation results from the successive coupling from differential mode to common mode and from common mode to the environment (or vice versa). The coupling attenuation is often assumed roughly as the sum of the unbalance attenuation of the pair and screening attenuation of the screen, (dB values).

Strictly speaking, however, the situation is more complicated. When coupling from differential mode to common mode, one wave propagates to the near end and a second wave to the far end. Both partial waves in turn couple into the environment with one wave each that propagates to the near and far end, see **Figure 8**.

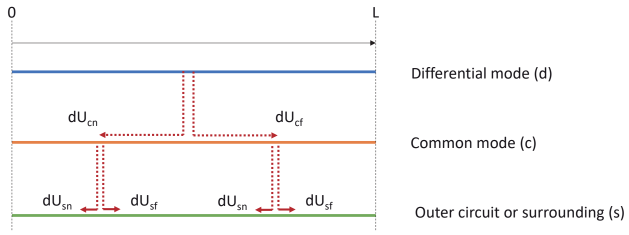


Fig. 8 — Successive coupling.

All partial waves must be summed up (integrated) in the correct phase over the entire coupling length. For homogeneous shields and with systematic coupling of counter-mode to common-mode operation and matching of the circuits, the coupling from differential mode to the environment results[14]:

$$T_n\sqrt{\frac{Z_s}{Z_d}} = \frac{\Re_{sn}\Re_{uf}}{Z_c Z_d}\frac{1}{\gamma_c-\gamma_d}\left\{\frac{e^{-(\gamma_s+\gamma_d)L}-1}{\gamma_s+\gamma_d}-\frac{e^{-(\gamma_s+\gamma_c)L}-1}{\gamma_s+\gamma_c}\right\}$$
$$+\frac{\Re_{sn}\Re_{un}}{Z_c Z_d}\frac{1}{\gamma_d+\gamma_c}\left\{\frac{e^{-(\gamma_d+\gamma_s)L}-1}{\gamma_d+\gamma_s}-\frac{e^{-(\gamma_d+\gamma_c)L}}{\gamma_s-\gamma_c}\left(e^{-(\gamma_s-\gamma_c)L}-1\right.\right. \tag{18}$$

$$T_f\sqrt{\frac{Z_s}{Z_d}} = \frac{\Re_{sf}\Re_{uf}}{Z_d Z_c}\frac{1}{(\gamma_d-\gamma_c)}e^{-\gamma_s L}\left\{\frac{e^{(\gamma_s-\gamma_d)L}-1}{(\gamma_s-\gamma_d)}-\frac{e^{(\gamma_s-\gamma_c)L}-1}{(\gamma_s-\gamma_c)}\right\}$$
$$+\frac{\Re_{sf}\Re_{un}}{Z_d Z_c}\frac{1}{(\gamma_d+\gamma_c)}e^{-\gamma_s L}\left\{e^{-(\gamma_d+\gamma_c)L}\frac{e^{(\gamma_c+\gamma_s)L}-1}{(\gamma_c+\gamma_s)}-\frac{e^{(\gamma_s-\gamma_d)L}-1}{(\gamma_s-\gamma_d)}\right\}$$

Where R$_s$ and Ru are the resulting coupling impedance of the screen or the unbalance attenuation.

$$\Re_{s_f^n} = \frac{Z_F \pm Z_T}{2} \qquad \Re_{u_f^n} = \frac{1}{2}\left(Z_d Z_c j\omega e \pm r\right) \tag{19}$$

Figure 9 shows the calculated coupling transfer functions of a shielded pair with a length of 50 m. And as is shown in **Figure 7**, a capacitance unbalance of 1.2 nF/km and a resistance unbalance of 4.5 Ω / km were calculated. A DC resistance of 13.6 Ω/km and a coupling inductance of 0.93 µH/km were assumed as the screen.

The coupling attenuation of the screen at high frequencies is 60 dB (CN_{cs}) at the near end and 43 dB (CF_{cs}) at the far end. At high frequencies, the envelope of the coupling attenuation from differential mode in the outer circuit at the far end (CF_{ds}) roughly corresponds to the sum of the envelope of unbalance attenuation at the far end (TCTL) and the coupling attenuation of the shield at the far end (CF_{cs}). At the near end, however, it corresponds to the sum of TCTL and the coupling attenuation of the shield at the near end (CN_{cs}).

The consideration shown in **Figure 9** applies to matched circuits. In the triaxial process, the outer circuit is not matched. At the near end there is a short circuit between the measuring tube and the screen of the DUT and the far end is terminated with the input impedance of the measuring receiver (VNA). The short circuit at the near end has the advantage that the near end coupling is fully reflected and superimposed on the far end coupling, i.e., only one measurement is necessary.

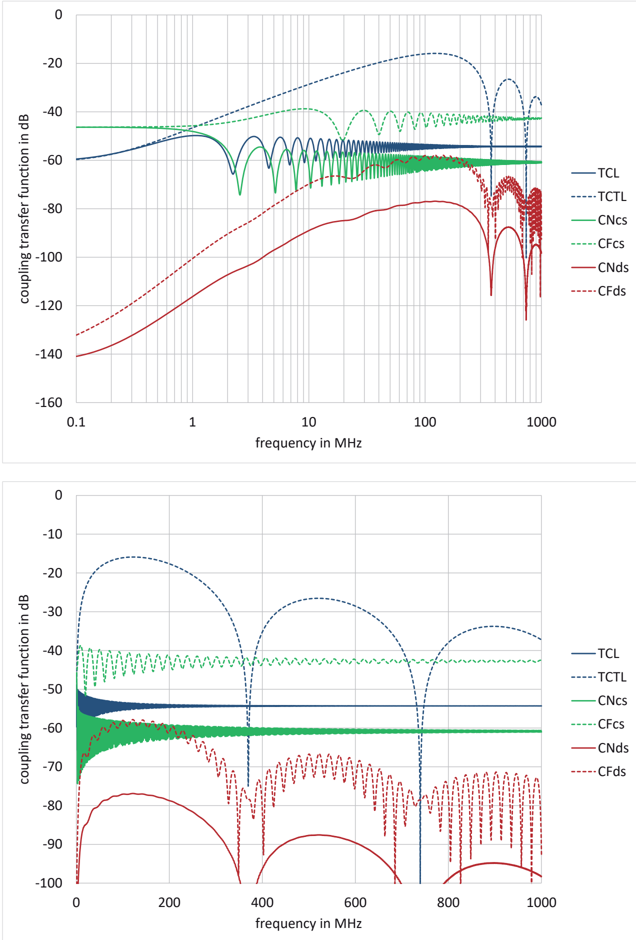


Fig. 9 — Calculated coupling transfer functions of a shielded pair with systematic coupling and 50 m length, with logarithmic and linear frequency scale.

The influence of the reflections due to the mismatch, as well as the effect of the intrinsic symmetry of the test set-up (e.g., symmetry transformer) and the noise level of the VNA can be taken into account by using the 6-port S-matrix of the screening effectiveness[14].

Figure 10 shows the calculated raw data of the unbalance attenuation at the near end (Scd11), the screening attenuation (Ssc21) and the coupling attenuation (Ssd21) of a single-pair shielded AWG23/1 cable for a coupling length of 5 m. The calculations were carried out for a triaxial test set-up with a short circuit at the near end of the outer circuit and termination with the VNA impedance (50Ω) at the far end. Furthermore, the mismatch by terminating the common mode (Z≈33Ω) with a terminating resistor of 25Ω was taken into account.

The noise level of the VNA was assumed to be 120 dB. The values of a good TP connecting unit were assumed to be inherent symmetry.

At low frequencies, the influence of the intrinsic unbalance and the noise level can be seen; at high frequencies, the superimposition of the near end coupling with the far end coupling can be seen through the mismatch in the outer circuit. The calculations correspond well with measurements

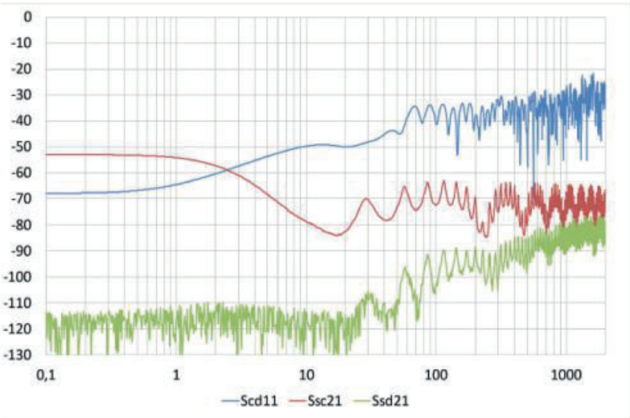


Fig. 10 — Calculated near unbalance attenuation (Scd11) as well as screening attenuation (Ssc21) and coupling attenuation (Ssd21) of a shielded single-pair AWG23/1 cable, coupling length 5 m, raw values.

(see **Figure 16**).

In the case of single-pair unshielded cables, the coupling attenuation is the same as the unbalance attenuation[13].

Test Procedure

Triaxial test procedure. The basic triaxial system according to **Figure 11** consists of two coupled systems; where the inner system is formed by the CUT and the outer system is formed by the tube and the outer conductor of the CUT; (the inner conductor of the outer system is the outer conductor of the inner system). At the near end, the screen of the CUT is connected to the tube by a short circuit. This principle is valid for both, coaxial and screened balanced cables.

The basic triaxial process is standardized as *IEC 62153-4-3* and *IEC 62153-4-4*, see **Figure 11**[22, 23].

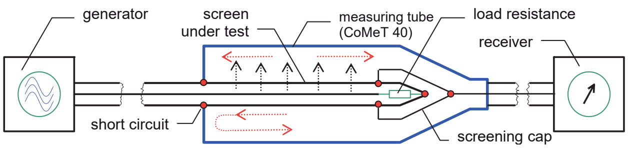


Fig. 11 — Basic triaxial tube procedure.

Coupling attenuation with virtual balun. To measure unbalance and coupling attenuation of balanced pairs, a differential signal is required. Balunless test procedures with a multi-port VNA and the application of the corresponding mixed mode S-parameters are established meanwhile also for triaxial coupling attenuation measurements[10, 11].

Figure 12 shows the test set-up for measuring the coupling attenuation according to *IEC 62153-4-9*[25]. The same test set-up is also used to measure the coupling attenuation at low frequencies, LFCA.

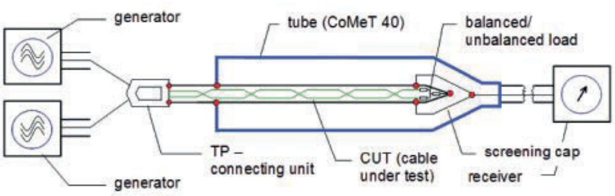


Fig. 12 — Coupling attenuation with virtual balun[25].

Figure 13 shows the test set-up for measuring the coupling attenuation and the LFCA of unshielded pairs according to *IEC 62153-4-9*, Amd1[26]. In contrast to the general triaxial method and for measuring the coupling attenuation, near and far coupling attenuation can be measured separately here. Because there is no short circuit between the shield and the tube, the power in the outer circuit corresponds to that of the common mode of the CUT.

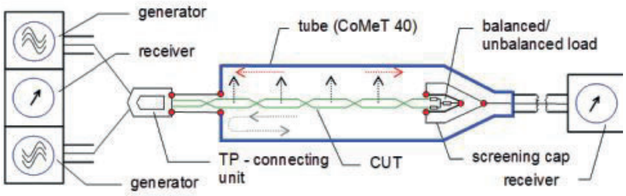


Fig. 13 — Measurement of the coupling attenuation of unshielded cables according to *IEC 62153-4-9* Amd1.

Low Frequency Coupling Attenuation (LFCA)

The lower cut-off frequency to measure coupling attenuation according to *IEC 62153-4-9Ed2* is given by:

$$f > \frac{c_o}{2 \times l \times \left|\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}\right|} \qquad (20)$$

c_0 = velocity of light
l = test length
ε_{r1}, ε_{r2} = dielectric constant of inner and outer circuit

That means, coupling attenuation on screened balanced pairs with manageable length can be measured only from about 30 MHz upwards. A test procedure for the EMC behavior of screened balanced cables at lower frequencies is needed.

EMC at lower frequencies of screened balanced pairs could be described by the differential Transfer impedance ZT_{diff}, which takes into account the transfer impedance of the screen and the unbalance of the pair. *ZT* of a cable screen is considered usually as invariant to the used test procedure and the test length. The "differential transfer impedance" however depends on the symmetry of the pair and will be therefore variant of the length and the symmetry.

In order not to confuse users and customers, ZT_{diff}, should not be used for balanced cables. It is also not useful for unscreened pairs.

Screened single pair cables. As an alternative, the coupling attenuation at low frequencies "Low Frequency Coupling Attenuation" LFCA for screened and unscreened pairs is introduced as a measure of the coupling attenuation at low frequencies[26]. The measurement setup is the same as for the coupling attenuation according to **Figure 12**, but the measurement can in principle be started at DC or a few kHz.

The Low Frequency Coupling Attenuation LFCA includes the unbalance attenuation of the pair, the coupling transfer impedance of the screen(if present) at lower frequencies and the screening attenuation of the screen at higher frequencies.

Figure 14, **Figure 15** and **Figure 16** show near and far end unbalance attenuation, screening attenuation and finally the raw values of the LFCA on a single-pair AWG 23/1 cable.

The length dependency and the frequency curve of the

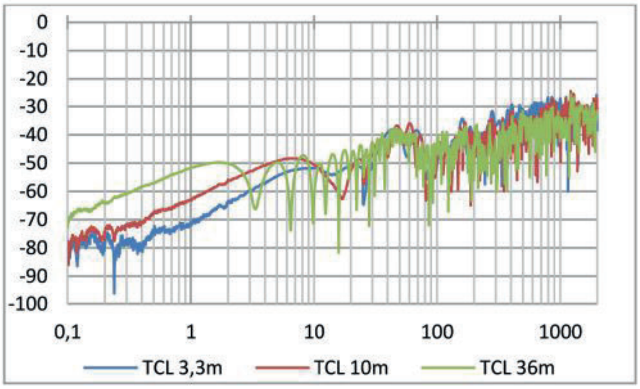


Fig. 14 — Near end unbalance attenuation TCL at different length of a screened single pair cable AWG23/1.

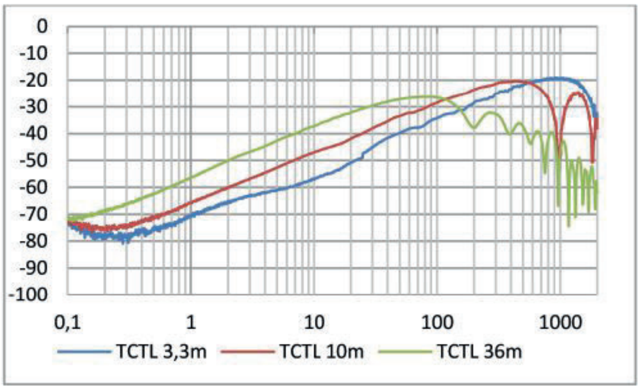


Fig. 15 — Far end unbalance attenuation EL TCTL at different length of a screened single pair cable AWG23/1.

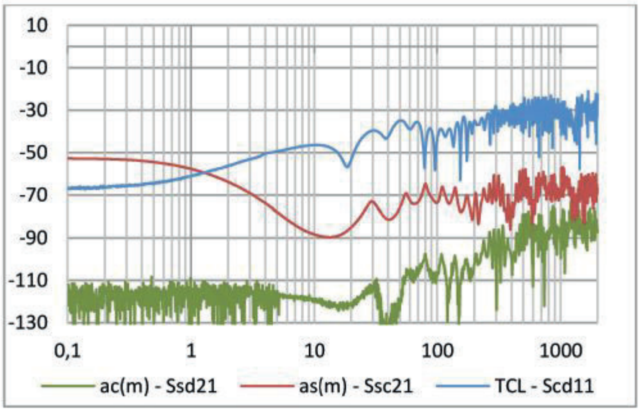


Fig. 16 — Near unbalance attenuation as well as screening attenuation and coupling attenuation of a single-pair shielded AWG23/1 cable, measuring length 5 m, raw values.

unbalance attenuation can be easily compared with the calculations according to Chapter 2.2. Furthermore, the resulting curve of the LFCA/CA shows good accordance with the modeling according to Chapter 3 (see **Figure 10**).

Unscreened single pairs. In the case of unscreened balanced pairs, the inner system is formed from the balanced pair (in differential mode) and the outer system from the measuring tube and the common-mode of the balanced pair. Since there is no screen on the unscreened pair, there is no short circuit at the near end as with a triaxial basic system according to **Figure 11** and **Figure 12**.

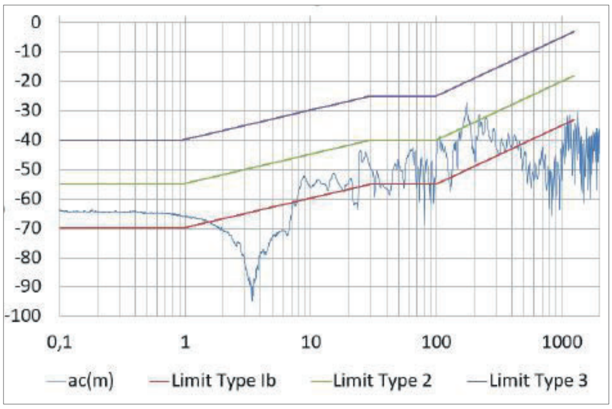


Fig. 17 — LFCA and CA on an unscreened single-pair cable, measuring length 3 m, in comparison with different limit value curves.

Therefore, coupling measurements can be carried out at both ends. **Figure 13** shows the configuration for measuring the near-end coupling[13].

The wave that propagates towards the near end is considered to be the near end coupling. It can be measured as Scd11, where Scd11 is also the near-end unbalance attenuation (TCL) of the unscreened balanced cable. This means the coupling attenuation of an unscreened balanced pair at the near end is equal to its unbalance attenuation. Same applies in principle to the far end; the coupling attenuation at the far end corresponds to the asymmetry attenuation TCTL at the far end[13].

Figure 17 shows an example of a measurement of LFCA and CA on an unscreened single-pair cable.

Different limit value curves are shown as a comparison. It can be seen that unscreened single-pair cables can also be classified in the proposed limit value categories Type I to Type 3

Evaluation of The Round Robin Test

Encouraged by the Single Pair Ethernet System Alliance[16], various single-pair screened cables are examined and measured in several laboratories of the partners involved. The measurement results obtained in this way form a basis for this report. **Figure 18** shows the measurement of LFCA and CA on a highly shielded AWG 26/7 cable. This cable is equipped with a longitudinal aluminum foil and a braid with an optical coverage of about 80%.

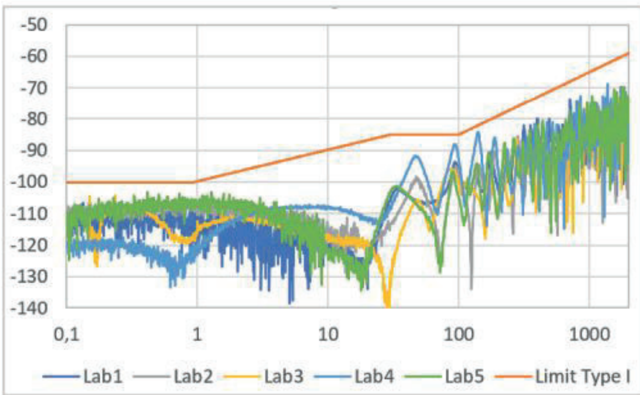


Fig. 18 — LFCA/CA measurements of different laboratories on samples of an AWG 26/7 cable of a production lot.

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It can be seen that the Type I limit is complied with according to the current draft standards. Type I is the limit with the most demanding values. It can be assumed that less complex screen constructions can meet weaker requirements. The measurement results of the different laboratories are easy to compare. This also suggests good reproducibility of the measurements.

An alien crosstalk measurement on a cable with a similar shield construction is shown in **Figure 19**. The limit values of the current edition of *IEC 61156-11* are met. It can therefore be assumed that cables that meet the requirements for LFCA/CA according to Type I also meet the alien crosstalk requirements.

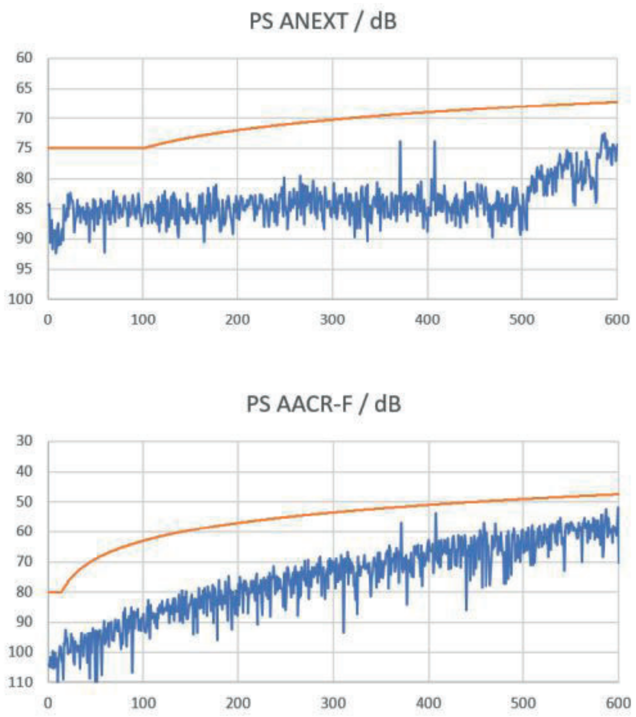

Fig. 19 — Alien-Crosstalk measurement "6 arround 1" on a highly shielded single-pair AWG 22/7 cable, measuring length 100 m.

Conclusion

In this article, the LFCA is reviewed in the context of the usual procedures for evaluating the screen properties and compared with simulation calculations. The results of a "round robin test" of balanced single-pair cables are compiled. Furthermore, the suitability of the LFCA measurement method for assessing the screening effect of unshielded balanced cables is discussed, since the standards mentioned for single-pair cabling and cables also include unscreened constructions.

LFCA and CA according to the triaxial method are well comparable between different laboratories, which implies good reproducibility. For the highly screened samples examined, the Type I limit proposed in the draft standards appears appropriate. It is obvious that lower shielding properties can be achieved with less use of material. The measured LFCA/CA curves are well comparable with the simulations.

The alien crosstalk measured on one of these samples meets the requirements of the currently published standard. It can therefore be assumed that cables with shielding properties according to Type I meet the requirements for alien crosstalk due to their design. Further investigations will have to show whether this also applies to Type Ib. WCTI

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