Screening effectiveness of unscreened balanced pairs

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***Abstract* - The screening effectiveness of screened balanced pairs is described by the transfer impedance Z_T in the lower frequency range and by the screening attenuation a_S and/or the coupling attenuation a_C at higher frequencies. The screening effectiveness of unscreened balanced pairs can be measured in principle with the same test-set-up as for screened balanced pairs as near and far end coupling. It could be shown, that the screening effectiveness of a single unscreened balanced cable is equal to its unbalance attenuation whereas the screening effectiveness of multiple unscreened pairs, e.g. for data transmission is the sum of its unbalance and the screening effect of the remaining pairs not under test. At low frequencies, screening effectiveness of unscreened single and multiple balanced pairs can be described and measured as "Low frequency coupling attenuation".**

Keywords – Balanced cables; Unscreened Twisted Pairs; Coupling Attenuation; Low frequency coupling attenuation; Transfer Impedance; Screening Attenuation; EMC; Triaxial Test Procedure; Triaxial Test set-up; Screening Effectiveness;

1 INTRODUCTION

The term "electromagnetic pollution" describes the constant increase of desired and undesired electro-magnetic radiation in our environment. Data networks are operated in various environments like office building, industrial factories or automotive. To guarantee that complex systems will not disturb each other, screening of the systems is highly recommended and measuring of EMC behaviour is mandatory. On the other hand, screening of balanced cables is perceived as expensive and the screen of the cable increases the overall weight of the complete system.

The question therefore arises, how good the screening effectiveness of unscreened balanced pairs is and what are suitable test procedures. Also, newer systems like Single Pair Ethernet may use the frequency band down to the kHz frequency range hence the need to evaluate the behaviour of unscreened balanced cables also at low frequencies and define appropriate test methods.

The following report describes the physical background of the screening effectiveness of screened and unscreened balanced pairs as well as appropriate test procedures to measure the screening effectiveness of unscreened single and multiple balanced pair cables, based on IEC 62153-4-9. The extension of IEC 62153-4-9 to measure screening effectiveness of unscreened balanced pairs is described and discussed. Test results are compared with absorbing clamp procedures according to IEC 62153-4-5.

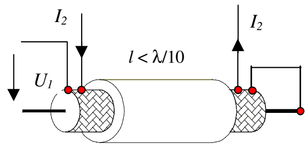
2 SCREENING-PARAMETERS

A. General

To protect a cable against external electromagnetic interference or to avoid radiation into the environment, it is surrounded with screens made of metal foils and/or braids. In case of balanced cables, also the overall symmetry of the single pairs contributes to the screening effectiveness in addition to the screen. The sole effect of the screen is described by the transfer impedance and the screening attenuation. The influence of the symmetry is grasped by the unbalance attenuation. The overall effect of the screen and the symmetry of the pair (for screened balanced cables) is described by the coupling attenuation.

B. Transfer impedance

For an electrically short screen, the transfer impedance Z_T is defined as the quotient of the longitudinal voltage U_1 induced to the inner circuit and the current I_2 fed into the outer circuit or vice versa, related to length in Ω/m or in mΩ/m, see fig.1.



$$Z_T = \frac{U_1}{I_2 \cdot l} \qquad (1)$$

Figure 1: Definition of transfer impedance

The test procedure to measure transfer impedance is described in IEC 62153-4-3 [2].

C. Screening Attenuation

The screening attenuation a_S is the measure of the effectiveness of a cable screen. It is the logarithmic ratio of the feeding power P_1 to the maximum radiated power $P_{r,max}$. With the arbitrary determined normalized value Z_S = 150 Ω [3] one gets:

$$a_S = 10 \cdot \lg\left|\frac{P_1}{P_{r,max}}\right| = 10 \cdot \lg\left|\frac{P_1}{P_{2,max}} \cdot \frac{2 \cdot Z_S}{R}\right| \text{ dB,} \qquad (2a)$$

$$a_S = 20 \cdot \lg\left|\frac{U_1}{U_{2,max}}\right| + 10 \cdot \lg\left[\frac{2 \cdot Z_S}{Z_1}\right] \text{ dB,} \qquad (2b)$$

where R is the input impedance of the receiver. More details are given in IEC 62153-4-1 and in IEC 62153-4-4 [1, 3].

With the arbitrary determined normalized value Z_S = 150 Ω one gets for screened balanced cables (in the common mode) the screening attenuation a_S:

$$a_S = 10 \cdot \lg \left| \frac{P_{\text{com}}}{P_{\text{r,max}}} \right| \text{ dB}, \quad (3a)$$

$$a_S = 20 \cdot \lg \left| \frac{U_{com}}{U_{2,\text{max}}} \right| + 10 \cdot \lg \left[\frac{2 \cdot Z_S}{Z_{\text{com}}} \right] \text{ dB}, \quad (3b)$$

D. Unbalance Attenuation

Screened balanced pairs may be operated in two different modes as shown in figure 2: the differential mode (balanced) and the common mode (unbalanced). In the differential mode one conductor carries the current +I and the other conductor carries the current -I; the resulting current in the screen is null. 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 [5, 6]. Under ideal conditions respectively with ideal cables both modes are independent from each other. However, under real conditions, both modes influence each other.

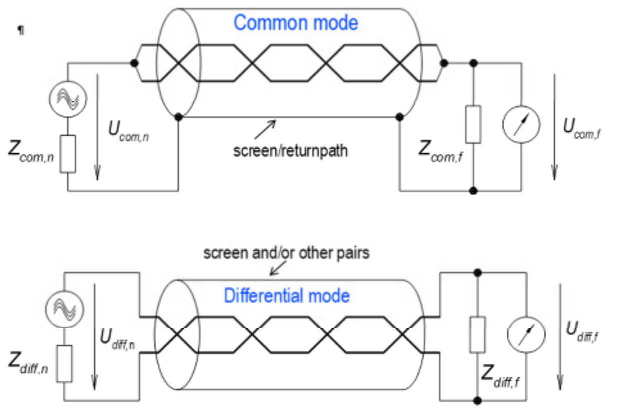


Figure 2: Common mode & differential mode of balanced pairs

The "Unbalance Attenuation" a_U of a pair describes in logarithmic scale how much power couples from the differential mode to the common mode and vice versa. It is the logarithmic ratio of the input power in the differential mode P_{diff} to the power which couples to the common mode P_{com}, [EN 50289-1-9Ed2].

$$a_u = 10 \cdot \lg \left| \frac{P_{\text{diff}}}{P_{\text{com}}} \right| \quad \text{dB}, \quad (4a)$$

$$= 20 \cdot \lg \left| \frac{U_{\text{diff}}}{U_{\text{com}}} \right| + 10 \cdot \lg \left[\frac{Z_{\text{com}}}{Z_{\text{diff}}} \right] \quad \text{dB}, \quad (4b)$$

U_{diff}, U_{com}: voltages in differential and in common mode,
Z_{diff}, Z_{com}: impedances in differential and in common mode.

According. to EN 50289-1-9Ed2, unbalance attenuation can be measured at near end as Transverse Conversion Loss, TCL and at far end as Transverse Conversion Transfer Loss TCTL.

Differences in the resistance of the conductors, in the diameter of the core insulation, in the core capacitance, unequal twisting and different distances of the cores to the screen are some reasons for the unbalance of the pair.

E. Coupling Attenuation

The coupling attenuation of screened balanced pairs describes the global effect against electromagnetic interference (EMI) and takes into account both the effect of the screen and the balance of the pair. In a first approach and at low frequencies, coupling attenuation a_C of a single balanced pair is considered as the sum of the unbalance attenuation a_U of the twisted pair and the screening attenuation a_S of the screen.

$$a_c = a_u + a_s \text{ dB}, \quad (5)$$

It is important to remind that the screening attenuation is defined as the maximum value of the measurement trace inside the relevant frequency range. Therefore, equation (5) should read $a_C = a_U + a_{S,\text{max}}$ [10].

3 Calculation of Unbalance Attenuation of Balanced Pairs

In the past the coupling attenuation of screened balanced cables was measured with a triaxial set-up according IEC 62153-4-9 where the cable under test has a length of 100m and the tube has a length in the range of 2 to 3m. The exceeding length of the cable is outside the tube with the use of a specific test head (open head) compared to the trial method to measure screening attenuation according IEC 62153-4-4. At that time the 100m sample length was defined to take into account the presumed length dependency of unbalance attenuation, (see figure 6).

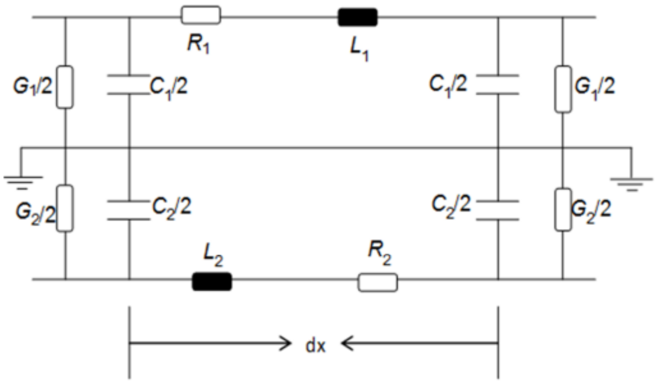


Figure 3: Equivalent circuit of a homogenous balanced cable with regular distribution of the primary transmission-line constants

Models for the analysis of the unbalance attenuation of pairs can be found for example, in [8] and [9]. Based on an equivalent circuit as shown in Figure 3, the longitudinal unbalance T_A and the lateral unbalance L_A can be defined as follows:

$$T_A = (G_2 + j\omega C_2) - (G_1 + j\omega C_1) \quad (6)$$

$$L_A = (R_2 + j\omega L_2) - (R_1 + j\omega L_1) \quad (7)$$

The terms of the unbalance coupling function can be formally written in the same way as for the crosstalk coupling function:

$$T_{u,n} = \frac{1}{4Z_{unbal.}} \int_{x=0}^{x=1} [T_A(x) \cdot Z_{unbal.}^2 + L_A(x)] \cdot e^{-(\gamma_{diff}+\gamma_{com})\cdot x} \cdot dx \tag{8}$$

For a homogenous (evenly distributed) cable, unbalance formula (8) can be expressed by the summing function S shown in Figure 4.

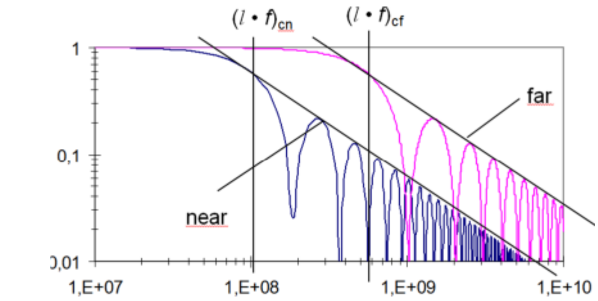


Figure 4: Summing function

$$T_{\substack{u,n\\u,f}} = (T_A \cdot Z_{unbal.}^2 \pm L_A) \cdot \frac{1}{Z_{unbal.}} \cdot \frac{1}{4} \cdot S_{\substack{n\\f}} \tag{9}$$

Neglecting the cable attenuation S can be expressed by the following equation:

$$S_{\substack{n\\f}} = \frac{\sin(\beta_{diff}\pm\beta_{com})\cdot\frac{1}{2}}{(\beta_{diff}\pm\beta_{com})\cdot\frac{1}{2}} \cdot e^{-\left(j\cdot(\beta_{diff}\pm\beta_{com})\cdot\frac{1}{2}\right)} \tag{10}$$

One may observe that the magnitude of the summing function is independent on the length. The length has only an influence on the periodicity. At high frequencies the asymptotic value approaches to:

$$S_{\substack{n\\f}} = \frac{2}{(\beta_{diff}\pm\beta_{com})\cdot l} \tag{11}$$

and at low frequencies the summing function becomes:

$$\left|S_{\substack{n\\f}}\right| \to 1 \tag{12}$$

Measurements of the behavior of the unbalance attenuation at different lengths and random disturbances are shown by way of example in [10].

4 TEST PROCEDURES

A. *Triaxial test procedure*

The basic triaxial system according to figure 5 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.

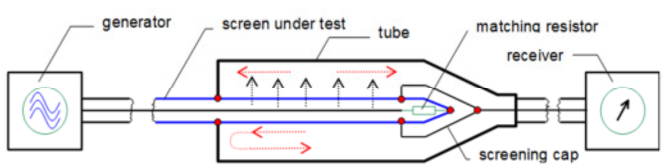


Figure 5: Basic triaxial tube procedure

The basic triaxial procedure is standardized as IEC 62153-4-3 and as IEC 62153-4-4 [2, 3].

B. *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 [9].

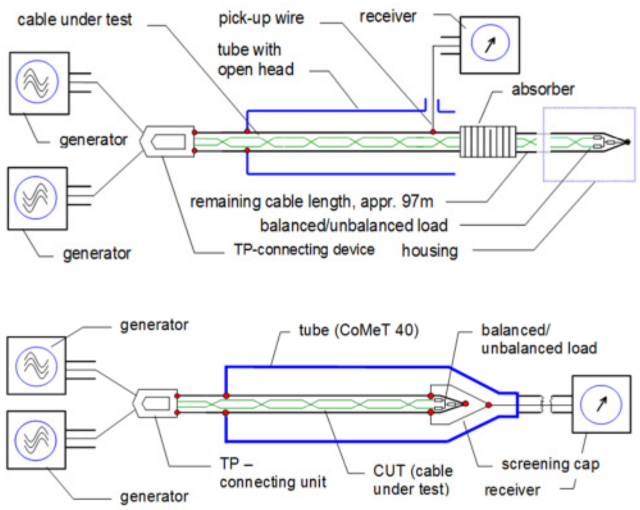


Figure 6: Coupling attenuation with virtual balun acc. to IEC 62153-4-9 with open head (upper fig.) and with standard head

C. *Screening effectiveness of unscreened balanced pairs*

The triaxial method has been proven as reference method for the measurement of screened balanced pair cables. Hence the idea to use it also for unscreened balanced pair cables. This makes the triaxial method the reference procedure for screening and coupling attenuation of coaxial, screened and unscreened balanced pair cables. Basically, it should be distinguished between single unscreened pairs and multiple unscreened pairs. In case of multiple unscreened pairs the EMC behavior respectively the test results depend on the treatment of the remaining pairs, i.e. load conditions. Figure 7 shows the principle triaxial set-up for balanced unscreened pairs.

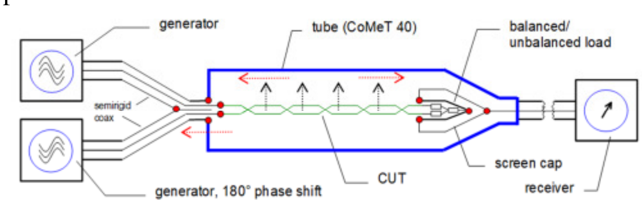


Figure 7: Screening effectiveness of unscreened pairs, principle set-up

The CUT is fed in the differential mode via two parallel semi rigid coax cables of equal length with the screens connected to the tube. Due to the signal conversion from the differential mode into the common mode a wave is travelling in both directions in the test section in the tube. In the basic triaxial system according to figure 5 the screen of the CUT is connected at the near end to the tube by a short circuit.

This principle is valid for both, coaxial (fig. 5) and screened balanced pair cables (fig. 6).

In case of unscreened balanced pair cables, the inner system is the CUT (in the differential mode) and the outer system is formed by the tube and the common mode of the CUT. Since there is no screen at the unscreened pair, there is no short circuit at the near end as in the basic triaxial set-up acc. to figure 5 and figure 6; hence coupling measurements can be performed on both ends. Figure 8 shows the configuration for the near end coupling attenuation measurement.

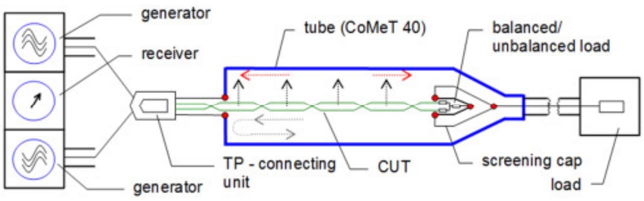


Figure 8: Unscreened pair near end coupling attenuation, Scd11

The wave propagating to the near end is considered as the near end coupling. It can be measured as Scd11 where Scd11 is also the unbalance attenuation at near end (TCL) of the unscreened cable under test (CUT)!

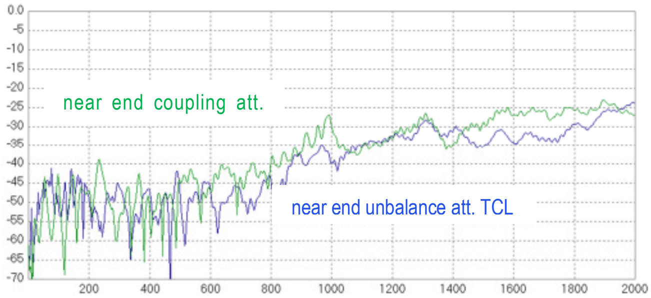


Figure 9: Near end coupling attenuation Scd11 and unbalance attenuation Scd11 of a single unscreened balanced pair

Figure 9 shows the unbalance attenuation (TCL) measurement (Scd11) of a 5m single unscreened pair, laid on a wooden table and the near end coupling attenuation measurement (Scd11) in the triaxial set-up according to figure 8.

Since the CUT is well centered in the tube and the distance of the tube wall to the CUT is about 20 mm, the influence of the tube diameter to the TCL is negligible; the curves of both measurements are nearly the same. Figure 10 shows the triaxial set-up for the far end screening attenuation (Ssc21) and the far end coupling attenuation (Ssd21) measurement of an unscreened pair.

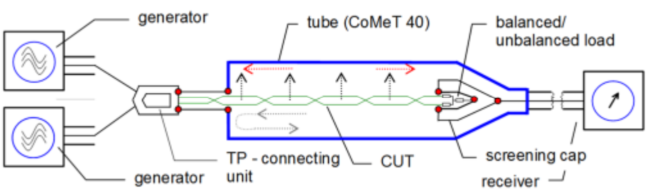


Figure 10: Unscreened pair far end coupling attenuation, Ssc21 & Ssd21

The CUT is matched with 50/50/25 Ohm; generating an impedance of 100 Ohm for the differential mode and an impedance of 50 Ohm for the common mode. The matching circuit (50 Ohm for the common mode) is connected to the 50 Ohm input impedance of the receiver of the network analyser. This generates an acting common mode impedance of 100 Ohm. One half of the common mode signal power is dissipated in the matching circuit. The other half is transmitted to the receiver. Therefore, the common mode related transmission results must be corrected with 3dB. Figure 11 shows the far end unbalance attenuation Scd21 and the far end coupling attenuation measurement Ssd21 of the same CUT with a length of 3,5m. The envelope curve of the far end coupling attenuation and far end unbalance attenuation show good accordance. Considering the correction of 3dB the max. values of the measured screening attenuation Ssc21 of the unscreened pair is nearly zero.

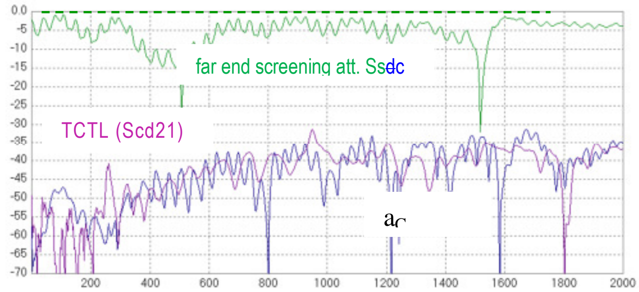


Figure 11: Far end screening attenuation Ssc21, far end coupling attenuation Ssd21 and far end unbalance attenuation Scd21 of a single unscreened pair

According to the above, it is proven by contemplation and by measurements, that the screening attenuation (Ssc21) of a single unscreened pair is nearly zero and that the coupling attenuation (Ssd21) of a single unscreened balanced pair is its unbalance attenuation TCL at near end and its TCTL at far end. Measuring of the unbalance of unscreened pairs itself was found to be difficult. Care should be taken not to introduce additional asymmetries at the feeding point respectively at the connection to the TP-connecting unit. Concerning measurement uncertainties, see also clause 6. It should be discussed with experts of IEC SC 46C/WG7 and with CLC TC46X/WG2 whether to establish correction procedures like gating for unbalance measurements.

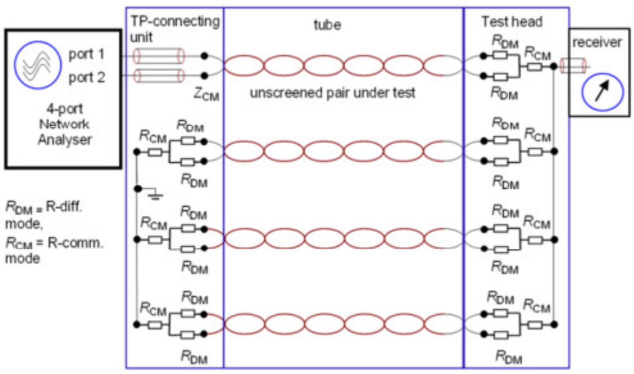


Figure 12: Basic configuration of coupling attenuation test of multiple unscreened pairs

Figure 12 shows the basic configuration for measuring of coupling attenuation of multiple unscreened pairs. All pairs of the CUT are matched at the far end with a PCB 50/50/25 and connected and matched at near end with a TP-connecting unit according to clause 4.D. The TP-connecting unit is connected to ground potential. The measurements of an unscreened Cat5e cable with the triaxial set-up according to figures 10 & 12 are shown in figures 13a to 13c. The screening attenuation (Ssc21) of about 10 to 15 dB can be explained by the influence of remaining pairs which acts as inner screen.

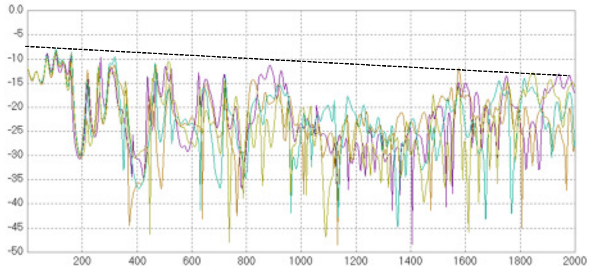


Figure 13a: Far end screening attenuation of an unscreened Cat5e acc. to figure 9, Ssc21

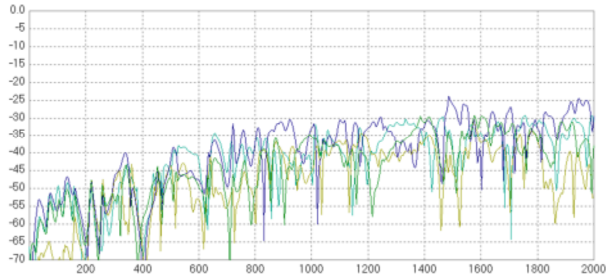


Figure 13b: Far end coupling attenuation of an unscreened Cat5e acc. to figure 9, Ssd21, lin

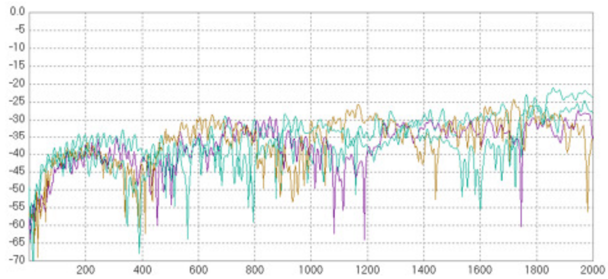


Figure 13c: Far end unbalance attenuation of an unscreened Cat5e acc. to EN 50289-1-9

This may be described by the fact that part of the energy coupled from the differential mode to the common mode of the pair under test is also coupled to the common mode and differential mode of the remaining pairs.

The coupling attenuation (Ssc21) is about 10 to 15 dB better than the far end unbalance probably also due to the screening effect of the remaining pairs with a trend to get equal values at higher frequencies.

D. *Test adapter & TP-Connecting unit*

When measuring Transfer impedance and Screening- or Coupling attenuation of connectors or cable assemblies, test adapters are required to connect the device under test (DUT) with the test set-up. Whereas it is an easy task to adapt coaxial DUTs by using broadly available coaxial adapters more effort must be spent on adapting differential DUTs. Figure 14 shows an example for such a TP-connecting unit which is described in [11]. Figure 15 shows the application of the TP-connecting unit to the near end of the triaxial test system when unscreened balanced pairs and connectors are tested.

Figure 14: TP connecting unit for four pairs

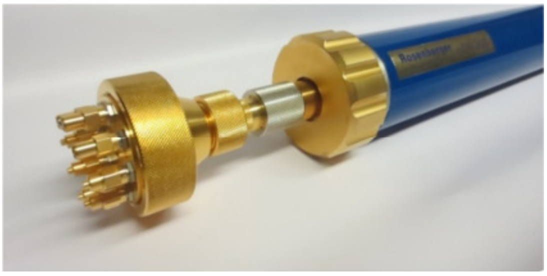


Figure 15: Near end tube connection for unscreened balanced pairs & connectors

Since the electrical performance of the test adapters may limit the sensitivity of the test set-up and possibly falsify the test results qualification tests shall be performed on the primarily contributing parameters.

Obviously important for both balanced and unbalanced adapters is the attenuation and the return loss since they affect the transmission of the test signal. When using balanced adapters for measuring the coupling attenuation of differential devices under test, (DUTs) the unbalance attenuation is another important parameter. This parameter describes the suppression of power conversion from the intended differential mode into the unintended common mode.

5 Low Frequency Coupling Attenuation

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

$$f > \frac{c_o}{2 \times l \times \left|\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}\right|} \qquad (9)$$

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 Z_{Tdiff}, which takes into account the transfer impedance of the screen and the unbalance of the pair. Z_T 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, Z_{Tdiff}, should not be used for balanced cables. It is also not useful for unscreened pairs.

Alternatively, the "Low frequency Coupling attenuation" $a_{C,lf}$ for screened and unscreened pairs is introduced. The test set-up is the same as the for coupling attenuation according to figure 8 but starting in principle from DC (or a few kHz).

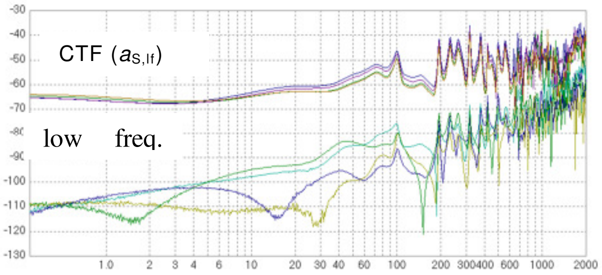


Figure 16a: Coupling Transfer Function Ssc21 & Low frequency Coupling attenuation, Ssd21, Cat7a

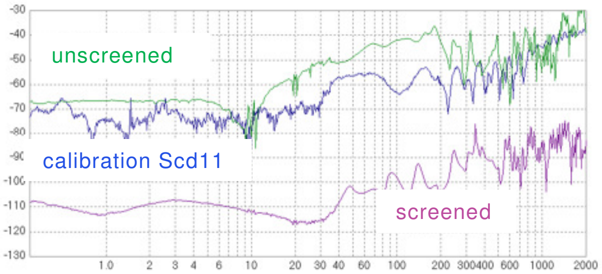


Figure 16b: Low Frequency Coupling attenuation of single balanced pairs, (screened & unscreened), 3m

Low frequency Coupling attenuation $a_{C,lf}$ includes the unbalance attenuation of the pair, the transfer impedance of the screen (if any) at lower frequencies and the screening attenuation at higher frequencies. Since the results of the $a_{C,lf}$ are depending on the length of the CUT and cannot (readily) extrapolated to other lengths, a test length must be specified to get comparable test results. Results of a suitable test length of 3m are shown in fig.16. Concerning measurement accuracy see chapter 6.

6 Measurement Uncertainties

Optimally calibrated and phase-stabilized measuring devices (VNA, test leads and connecting units) show a specific frequency-dependent course of a system-mode conversion. This is at low frequencies between -80 and -70dB and increases with increasing frequencies at about -60 to -40dB. Depending on the phase position, this system-mode conversion superimposes the mode conversion of the test object constructively or destructively. The result of the measurement is thereby falsified and, in particular, very strong if the amount of the mode conversion of the test object approaches or even undershoots the amount of the system mode conversion. All Low frequency Coupling attenuation measurements $a_{S,lf}$ (figures 13 & 16) may be victims of such overlays. The system values should therefore be recorded and included in the measurement uncertainty analysis.

An estimation of the system mode conversion can be done by e.g. recording the reflected mode conversion parameter Scd11 with a TP-connecting unit having an open loop.

7 Absorbing Clamp Procedure

The measurement of screening- or coupling attenuation of balanced cables can be achieved either with the absorbing clamp method according to IEC 62153-4-5, [4] or with the triaxial test set up according to IEC 62153-4-9, [5]. Figure 17 shows the test set-up to measure the screening attenuation of an unscreened balanced pair with the absorbing clamp procedure according to draft IEC 62153-4-5Ed2.

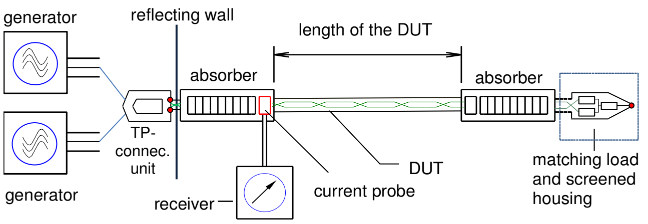


Figure 17: Principle of absorbing clamp procedure, draft IEC 62153-4-5Ed2

The VNA was calibrated by a full 4-port calibration. The absorbing clamp set-up was calibrated carefully according to IEC 62153-4-5; different clamp positions were measured and the max. values were taken from each position. Whereas the triaxial measurement of the screening attenuation of an unscreened single pair is close to zero (fig. 8), the screening attenuation measured with absorbing clamp MDS 21 shows very different values.

In fact, when measuring the screening attenuation at the near end one is measuring the insertion loss of the absorber of the clamp (*a(clamp.inp. att.abs(A-B)/dB*). Hence in figure 18 the blue curve for the near end screening attenuation is almost identical to the orange curve for the insertion loss of the absorber. At the far end the values are even higher due to the attenuation of the common mode.

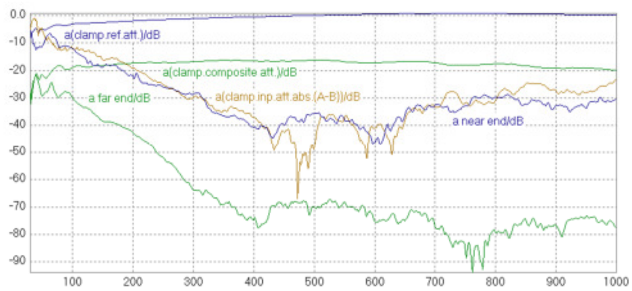


Figure 18: Screening att. of a single unscreened balanced pair with absorbing clamp MDS 21

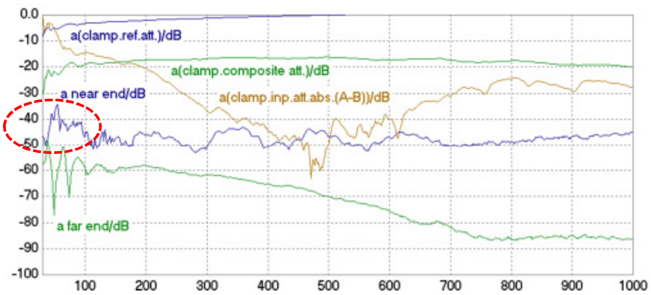


Figure 19: Coupling att. of a single unscreened balanced pair with absorbing clamp MDS 21

The coupling attenuation measured with absorbing clamp MDS 21 is shown in figure 19. It deviates from the measured coupling attenuation with triaxial set-up as well as from the measured far and near end unbalance attenuation (fig. 9 & 11) with poor values below 100 MHz. The reasons for this behaviour at lower frequencies is the low insertion loss of the absorber in the lower frequency range and the related wave reflections.

Measuring with absorbing clamps shows different drawbacks against the measurement with the triaxial test set-up. Calibration of composite loss and reflection loss of the clamps is complicated and depends on the characteristics of the DUT. Furthermore, the measurement with absorbing clamps shall be performed in a screened room if necessary for higher screening values to avoid environmental influences. Especially in the frequency range up to 100 MHz, the composite loss of the clamps is considerable (20dB) which reduces the dynamic range, possible disturbances from radio stations are also considerable and the different weaknesses of the clamp method are superimposing. With the triaxial test set-up with standard test head environmental influences are excluded by the set-up itself.

8 Conclusion and Outlook

Coupling attenuation of screened balanced pairs can be measured according to IEC 62153-4-9.

It could be shown, that also coupling attenuation of unscreened balanced pairs can be measured easily with the triaxial test procedure and in principle with the same set-up as for screened pairs according to IEC 62153-4-9 and over the complete frequency range.

Deviant from IEC 62153-4-9 the coupling attenuation of unscreened balanced pairs can be measured as near end coupling (Scd11) and as far end coupling (Ssd21).

In the lower frequency range below 30 MHz EMC can be measured as “Low frequency Coupling attenuation” $a_{C,lf}$ from less than 9 kHz upwards with the same set-up as for higher frequencies.

On single unscreend balanced pairs, coupling attenuation equals its unbalance attenuation, TCL at near end and TCTL at far end.

On multiple unscreened balanced pairs, coupling attenuation is the sum of its unbalance attenuation, TCL at near end and TCTL at far plus the screening effect of the remaining pairs not under test.

IEC 62153-4-9 will be amended accordingly.

9 References

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