History and recent trends of Triaxial test procedure

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Abstract

Measuring of the transfer impedance Z_T of cables, connectors and assemblies with the triaxial test procedure was introduced by Schelkunoff 1934; the triaxial procedure is still prevailing and in use worldwide.

Latest developments of the triaxial test procedure are "Balunless measurement of coupling attenuation" based on IEC 62153-4-9Ed2, the "Triaxial Absorber cell" acc. to IEC 62153-4-15Ed2 up to and above 3 GHz and the "Conversion of transfer impedance into screening attenuation and vice versa" acc. to IEC 62153-4-16.

The following report gives an overview over the history of EMC measurements on cables, connectors and assemblies as well as of the recent trends of triaxial test procedures.

Newly developed TP-connecting devices as well as newly designed test adapters for different types of balanced connectors and cable assemblies are introduced.

New challenges among others are the measurement of the coupling attenuation of unscreened balanced pairs and the extension of the frequency range of the triaxial procedure up to 9 GHz and more as required e.g. by the automotive industry. First promising results are presented and discussed.

Keywords: EMC; Screening effectiveness; Transfer impedance; Screening attenuation; Coupling attenuation; Triaxial test procedure; Triaxial test set-up; Unbalance attenuation; Twisted pairs, Balanced pairs

1. Introduction

EMC of screened cables, connectors, assemblies and components is described by the transfer impedance Z_T in the lower frequency range and by the screening attenuation a_S or the coupling attenuation a_C at higher frequencies.

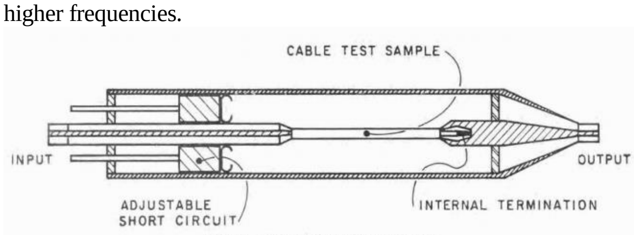


Figure 1 – Measuring of transfer impedance – Zorzy/Muehlenberger 1961

Measuring of the Transfer impedance Z_T of cables, connectors and assemblies with the triaxial test procedure was introduced by Schelkunoff 1934; and developed further by numerous experts worldwide over the last 84 years.

The development of screening attenuation measurement in the higher frequency range with the triaxial test procedure was initiated 1990 by Otto Breitenbach.

Meanwhile the triaxial procedure has been extended to further parameters like coupling attenuation a_C on balanced cables and assemblies as well as to measure the EMC of larger components, e,g. cable assemblies for electric vehicles, taking into account new measurement technologies. Several triaxial test procedures for different applications are standardized international as IEC 62153-4-n series.

2. History of screening measurements

2.1 First EMC concepts

1934 - Schelkunoff, (probably) first mention the concept of transfer impedance for cable screens [1].

Further early description of transfer impedance of different cable screen constructions including a triaxial test procedure is given 1936 by H. Ochem [2].

A complete description of screening phenomena was given by Heinrich Kaden, in "The book of Kaden" 1950 respectively 1959, [3]. W. Klein also described screening phenomena in his book "Die Theorie des Nebensprechens auf Leitungen" in 1955, [4].

1956 H. Jungfer described Z_T measurement [5] wheras L. Krügel described the screening effectiveness of flexible shields in the same year [6].

1961 John Zorzy & R.F. Mühlenberger described a triaxial test set-up to measure Transfer impedance up to 7,5 GHz, [7]. The set-up was equipped with a sliding wall to shorten the active test length of the cable under test (CUT), see figure 1. The procedure is also described in MILPRF39012.

Different laboratories designed their own triaxial set-up to measure transfer impedance at that time, e.g. at Helsinki University of Technology 1962 by Lauri Halme.

E. Homann described procedures for braid optimization (1968) [8]. Vance (1974) [9], Tyni (1976) [10] and Kley (1991) [11] among others described models for the calculation of coupling phenomena of braided screens. These models are still the basis for relevant simulation software.

Although analytical models of Z_T are useful for shielding analysis, measurements are still the most reliable method of determining the Z_T due to the complex structure of braided shields.

2.2 Absorbing clamp procedure

With the first cable-TV networks in the nineteen-seventies, a procedure to measure EMC on CATV cables towards higher frequencies was needed. Although a triaxial procedure to measure transfer impedance on short cable length up to 1 GHz was published in August 1984 as Amendment No. 1 to IEC 96-1:1971, the triaxial procedure was considered unsuitable for higher frequencies at that time. A test result in decibels (dB) instead of milli-Ω/meter (mΩ/m) was desired.

Meyer de Stadelhofen described the absorbing clamps first in Techn. Mitt. PTT 1969 [12]. CISPR 8, Report No. 47 describes the absorbing clamp procedure as well as procedures with antennas to measure screening attenuation on cable screens in 1975.

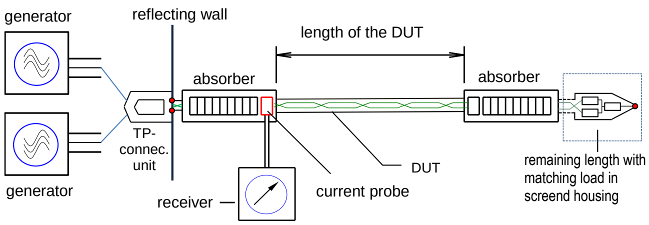


Figure 2 – Screening- or Coupling attenuation with absorbing clamps and virtual balun

Based on the clamps of Meyer de Stadelhofen, the absorbing clamp procedure up to 1 GHz was developed by the German Committee UK 412.3 and published in January 1983 as DIN 47250 Teil 6: "Messung des Schirmungsmaßes koaxialer Kabel zwischen 30 und 1000 MHz, Verfahren mit Absorberzangen".
International the clamp procedure was prepared by IEC SC 46A/WG1, (later IEC TC 46/WG5) with Lauri Halme as Convenor and published by IEC in June 1993 as amendment 2 to IEC 96-1:1986.

Based on DIN 47250 Teil 6 the first computer controlled test station to measure screening attenuation up to 1 GHz with networkanalyzer R&S ZPV and clamp MDS 21 was established at bedea laboratories in Asslar, Germany in 1985.

The revision of the clamp procedure with the extension to measure also the coupling attenuation on unscreened and screened balanced cables up to 1 GHz was prepared by CLC TC46X/WG3 and published as EN 50289-1-6:2002. It was overtaken by IEC as IEC 62153-4-5:2006. The clamp procedure as shown in figure 2 is currently under revision by IEC TC 46/WG5 as 2nd Edition, including balunless measurements up to 2,4 GHz with absorbing clamp MDS 22.

2.3 Line injection method

The line injection method which was developed by experts of the Swiss Telecom was first mentioned by Bernhard Eicher at al - 1988 [13]. The procedure was standardized 1993-03 in IEC 96-1Amd2, as line injection procedure, together with the absorbing clamp procedure.

The basic principle of the line injection method is simple; an unscreened wire is placed close to the (CUT) and "injects" RF energy into the CUT. The energy which couples into the CUT is measured at near and far end as transfer impedance.

Although the principle is simple, one has to perform at least 8 different measurements to find the worst case (near and far end and 4 different positions around the circumference); The cut off frequency of the procedure depends on the propagation velocities of inner and outer circuit and the impedance matching (1). It reaches from about 50 MHz to about 1 GHz.

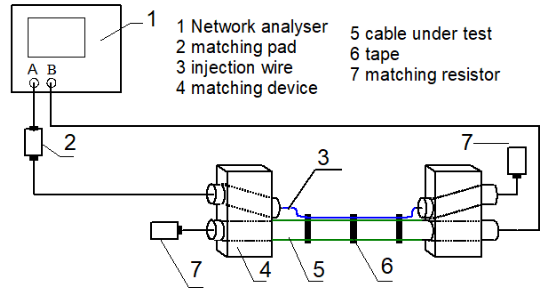


Figure 3a – Transfer impedance with "line injection"-procedure

Often the maximum frequency for transfer impedance of the line injection method is mixed up with screening attenuation.
With the dielectric constants ε_{r1}, ε_{r2} of outer and inner circuit respectively the propagation velocities v_1, v_2 and the test length L_c, the cut off frequency f_c is given by:

$$f_c = \frac{c}{\pi \cdot L_c \cdot \left|\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}\right|} = \frac{1}{\pi \cdot L_c \cdot \left|\frac{1}{v_1} - \frac{1}{v_2}\right|} \qquad (1)$$

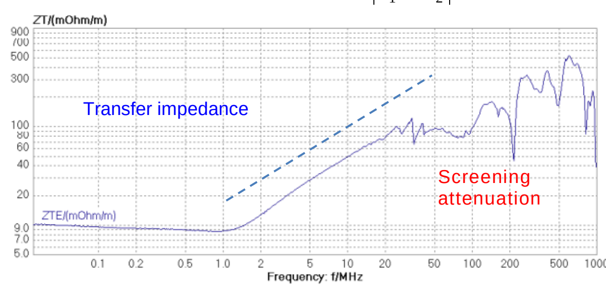


Figure 3b – Transfer impedance of a RG 214 with "line injection"- procedure, 1m near end

According to IEC 62153-4-6, measured Z_T values may be extra-polated with double log. straight line up to 100 MHz (fig. 3b). Screening attenuation is not defined for the line injection method. Reaching the required matching of the injection wire of 20 dB on both ends could be critical.

Also in 1988 the summing function $S_{n,f}$ (2) shown in figure 4 was introduced by Lauri Halme [14].

$$\left|S_{\frac{n}{f}}\right| = \frac{\left|2\sin\left(\frac{(\beta_1 \pm \beta_2).L_c}{2}\right)\right|}{(\beta_1 \pm \beta_2).L_c} \qquad (2)$$

The summing function which is in principle a sinx/x function describes the coupling (crosstalk) behavior between two lines under matched conditions over the frequency.

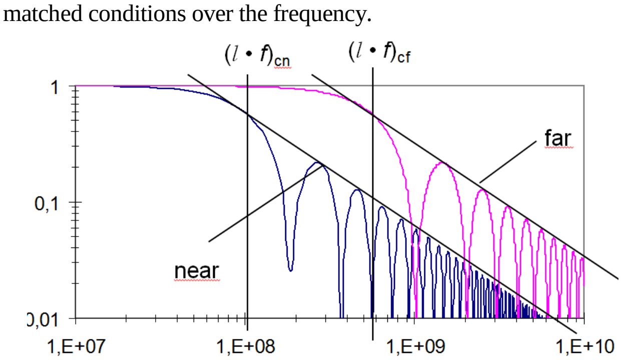


Figure 4 - Summing function

It includes the phase relation β_1, β_2 of the inner and the outer circuit and the test length L_c. The result of the summing function gets one at low frequencies and shows the oscillating reaction at higher frequencies.

3. Progress of triaxial test procedure

Although the clamp procedure offered a possibility to measure screening attenuation from 30 MHz to 1 GHz in dezibels [dB], operators of the clamps mostly had some doubts about plausibility and repeatability of the test results. Due to the undefined outer circuit of the absorbing clamp method, the test results obtained at different places and laboratories could vary by at least ± 6dB [IEC 62153-4-5].

1990 Otto Breitenbach, Kabelmetal Nuremberg, Germany, started the research to measure screening effectiveness with the triaxial procedure also in the higher frequency range.

Breitenbach realized, that the max. values of the resonances of the triaxial procedure at higher frequencies could be used as measure of the screening attenuation up to and above 3 GHz [15, 16] and [IEC 46A/(Germany)62], see figure 5.

His research was supported by Thomas Hähner as young engineer. After discussion with the German National Committee UK 412.3 and with IEC TC 46/WG5 the document IEC 46A/(Germany)62 was submitted 1994-01 as new work item proposal, NP to IEC SC 46A.

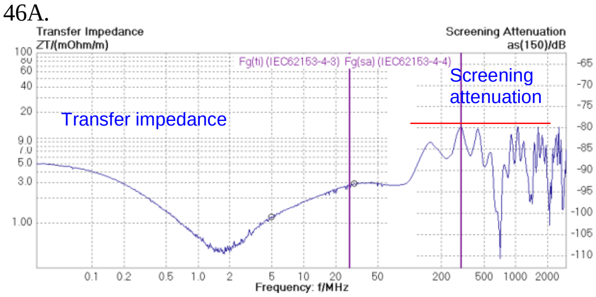


Figure 5 – Coupling Transfer Function CTF (a_S & Z_T) of a coaxial RG 214

Next steps to standardize the new procedure "Shielded screening attenuation test method for measuring the screening attenuation a_S up to and above 3 GHz" were 46A/269/CD - 1996-08-30, 46A/320/CDV 1998-01-23, and 46A/349/FDIS 1999-04-30. In August 1999, Amendment 1 to IEC 61196-1 was published including the new triaxial procedure. Transfer impedance at lower frequencies and Screening attenuation up to and above 3 GHz could be measured now with the triaxial test set-up with only one test procedure, see figure 6.

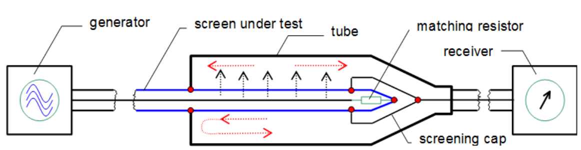


Figure 6 - Basic triaxial tube procedure according to IEC 62153-4-3 /-4-4

In parallel to the theoretical work of Otto Breitenbach and Thomas Hähner, the hardware of the triaxial set-up was developed and improved at the bedea RF&EMC laboratories, Asslar, Germany with Bernhard Mund as head of department. Significant developments were the separated test head, the jam devices for the short circuit at the near end and the matched screening case with clamping jaws. With these improvements sample preparation became much easier.

Based on the work of bedea, a professional triaxal test set-up is manufactured by Rosenberger, Tittmoning, Germany since more than 20 years and distributed by bedea, Asslar, Germany as **Co**upling **Me**asuring **T**ube system (CoMeT).

In the aftermath of the new standard for screening attenuation, further applications based on the triaxial procedure were established, see table 2. Meanwhile more than 300 new triaxial test set-ups are in use worldwide. Further applications and improvements of the triaxial procedure are in progress at IEC TC 46/WG5.

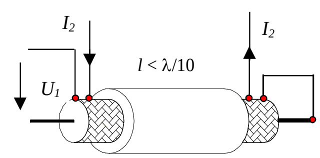
In 2000 screening classes for CATV cables according to the EN 50117 series were introduced by CLC 46XA and overtaken later also from IEC SC 46A for CATV cables according to the IEC 61196 series.

For the measurement of transfer impedance and screening attenuation the triaxial procedure according to IEC 62153-4-3 and -4-4 was determined as the only permissible test procedure. The absorbing clamp procedure is not accepted for measuring EMC on CATV cables acc. to EN 50117 and IEC 61196 series due to the larger uncertainties of the clamp procedure. The same applies also to coaxial cable assemblies like TV receiver leads according to the IEC/EN 60966 series.

4. Physical background

4.1 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 by the current I_2 fed into the outer circuit- or vice versa, related to length in Ω/m or in mΩ/m, see fig. 7.



$$Z_T = \frac{U_1}{I_2 \cdot l} \qquad (3)$$

Figure 7: Definition of transfer impedance

4.2 Screening attenuation

The screening attenuation a_S is the measure of the screening effectiveness of a cable screen. It is the logarithmic ratio of the feeding power P_1 to the max. radiated power P_2.

$$a_S = 10 \cdot \log|P_1 / P_2| = 20 \cdot \log|U_1 / U_2| \quad \text{dB} \qquad (4)$$

With the arbitrary determined normalized value Z_S = 150 Ω (see IEC 62153-4-4) the input voltage U_1, the output voltage $U_{2,max}$ and the characteristic impedance Z_1 of the cable under test one gets:

$$a_S = 20 \cdot \lg\left|\frac{U_1}{U_{2,\max}}\right| + 10 \cdot \lg\left[\frac{2 \cdot Z_S}{Z_1}\right] \quad \text{dB} \qquad (5)$$

4.3 Unbalance attenuation

The unbalance attenuation a_U of a balanced pair describes in logarithmic scale how much power is coupled from the differential mode P_{diff} to the common mode P_{com} or vice versa.

$$a_u = 10 \cdot \lg\left|\frac{P_{\text{diff}}}{P_{\text{com}}}\right| = 20 \cdot \lg\left|\frac{U_{\text{diff}}}{U_{\text{com}}}\right| + 10 \cdot \lg\left[\frac{Z_{\text{com}}}{Z_{\text{diff}}}\right] \quad \text{dB} \quad (6)$$

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

Unbalance attenuation can be measured at near end as Transverse Conversion Loss, TCL and at far end as Transverse Conversion Transfer Loss TCTL [EN 50289-1-9].

4.4 Coupling attenuation

The coupling attenuation a_C of screened balanced pairs describes the screening effectiveness respectively the global effect of balanced or twisted pair (TP) cables against electromagnetic interference (EMI) and takes into account the effect of the screen and the symmetry of the pair [17]. With the arbitrary determined normalized value Z_S = 150 Ω (see IEC 62153-4-9) the input voltage U_1, the output voltage $U_{2,max}$ and the differential impedance Z_{diff} of the cable under test one gets:

$$a_c = 20 \cdot \lg\left|\frac{U_{diff}}{U_{2,max}}\right| + 10 \cdot \lg\left[\frac{2 \cdot Z_S}{Z_{diff}}\right] \quad \text{dB} \qquad (7)$$

At first approach and at low frequencies, the coupling attenuation a_C of a single balanced pair can be considered as sum of the unbalance attenuation a_U of the pair and the screening attenuation a_S of the screen [17].

$$a_c \approx a_u + a_s \quad \text{dB} \qquad (8)$$

Details of the triaxial procedure as well as physical basics are given in [14, 15, 16, 17] and in IEC TS 62153-4-1.

5. Recent trends of triaxial procedure

5.1 Balunless test procedures

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 procedures, see e.g. figure 8 [17].

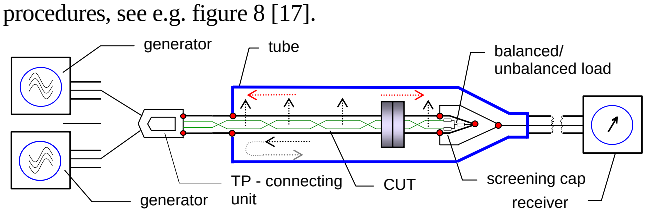


Figure 8 – Coupling attenuation with virtual balun

IEC 62153-4-9, coupling attenuation on screened balanced cables was revised recently; edition 2 was published 2018-05-29. The revised version contains the measurement of coupling attenuation with open test head as well as the measurement with standard test head up to 2 GHz, see fig. 8.

5.2 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. But 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 set-up for coupling attenuation according to fig. 8, but starting in principle from DC.

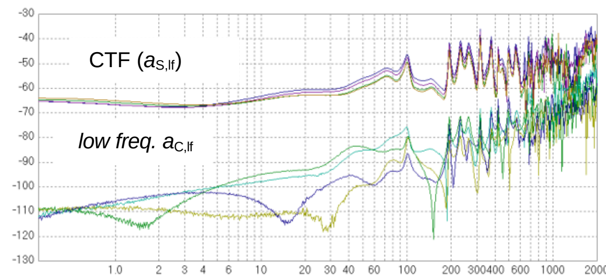


Figure 9a – Coupling Transfer Function Ssc21 & Low frequency Coupling attenuation, Ssd21, Cat7a

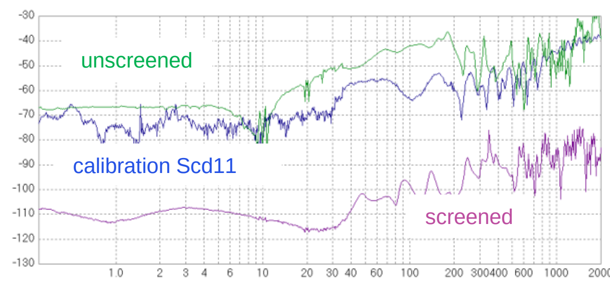


Figure 9b - Low frequency Coupling attenuation of single balanced pairs, (screened & unscreened), 3m

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.9. Concerning test accuracy see 9.2.

5.3 Screening effectiveness of unscreened balanced pairs

In order to accept the triaxial procedure as reference procedure, some experts demand to measure also the screening effectiveness of unscreened balanced pairs with the triaxial test set-up.

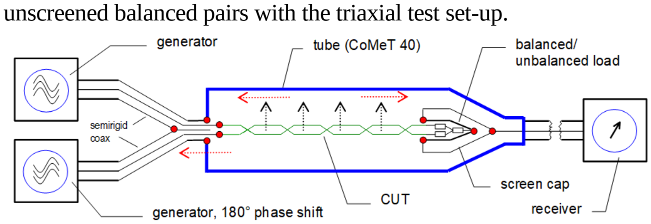


Figure 10 - Screening effectiveness of unscreened pairs, principle set-up

Basically it should be distinguished between single unscreened pairs and multiple unscreened pairs. In case of multiple unscreened pairs EMC behavior respectively test results depend on the treatment of the remaining pairs, e.g. grounded or not.

Grounded remaining pairs may act as an "inner" screen !

Figure 10 shows the principle triaxial set-up for balanced unscreened pairs. 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.

The basic triaxial system according to figure 6 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.

In case of unscreened balanced cables, the inner system is the CUT (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 fig. 6; hence coupling measurements can be performed on both ends.

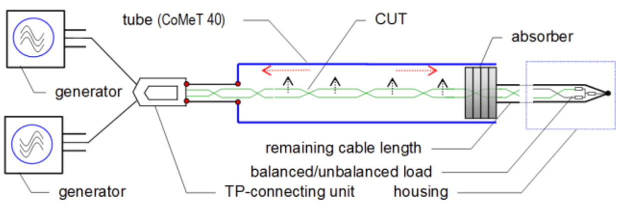


Figure 11 – Unscreened pair near end coupling attenuation with absorber, Scd11

Figure 11 shows the configuration for the near end coupling attenuation measurement. Absorber are used for proper matching at the far end. The reflection factor (time domain) in the outer circuit (Scc11) was measured at the absorber end to be less than 0,3 (10dB).

The back travelling energy at the near end in figure 11 is considered as the near end coupling. It can be measured as Scd11 where Scd11 is also the unbalance attenuation (TCL) of the unscreened cable under test (CUT) at near end !

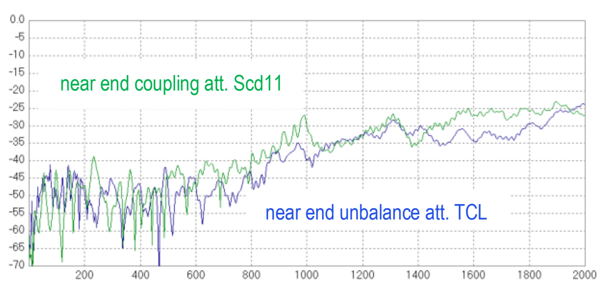


Figure 12 – Near end coupling attenuation and TCL of an unscreened balanced pair, Scd11

Fig. 12 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 fig. 11.

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 to the TCL is negligible; the curves of both measurements are nearly the same.

Near end coupling attenuation of an unscreened balanced pair = its unbalance attenuation, TCL !

Figure 13 shows the triaxial set-up for the far end screening attenuation (Ssc21) and the far end coupling attenuation (Ssd21) measurement of an unscreened pair.

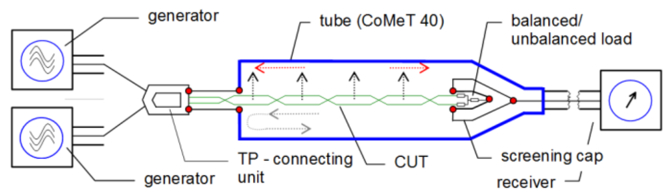


Figure 13 – Unscreened pair far end coupling attenuation, Ssc21 & Ssd21

The CUT is matched with 50/50/25 Ohm; that means 100 Ohm for the differential mode and 50 Ohm for the common mode. The 50 Ohm common mode resistor is in series to the receiver of the network analyser.

With the correction of 3dB due to the 50 Ohm series resistor the max. values of the measured screening attenuation (Ssc21) of the unscreened pair is nearly to zero (fig. 14).

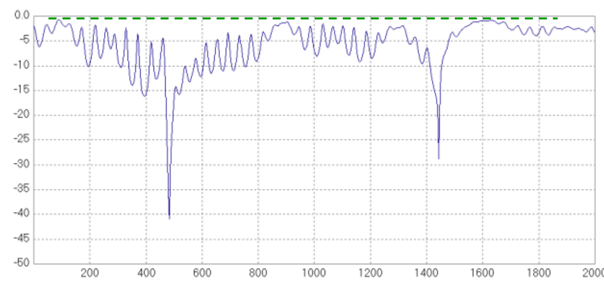


Figure 14 – Far end screening attenuation of an unscreened pair acc. to figure 13, Ssc21

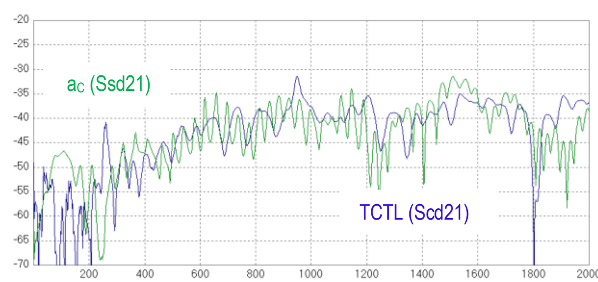


Figure 15 – Far end coupling attenuation Ssd21 & far end unbalance att. Scd21 of an unscreened pair

Figure 15 shows the far end unbalance attenuation Scd21 and the far end coupling attenuation measurement Ssd21of the same CUT with a length of 3.5m. The envelope curve of coupling attenuation and far end unbalance attenuation show good accordance.

According to the above, it is proven by contemplation and by measurements, that the screening attenuation (Ssc21) of an unscreened pair is nearly zero and that the coupling attenuation (Ssd21) of an 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 [21], see also 9.2.

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.

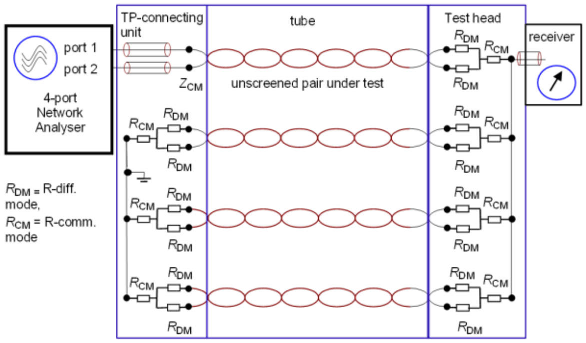


Figure 16 – Basic configuration of coupling attenuation test of multiple unscreened pairs

Figure 16 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 [17] and connected and matched at near end with a TP-connecting unit according to 5.4 [18]. The TP-connecting unit is connected to ground potential.

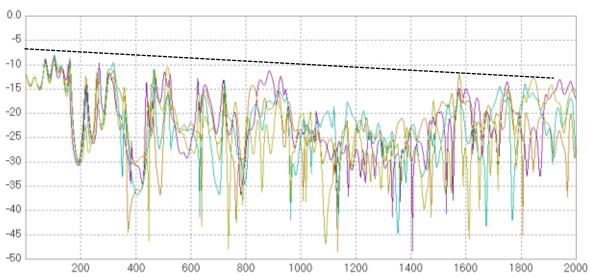


Figure 17a – Far end screening attenuation of an unscreened Cat5e acc. to figure 13, Ssc21

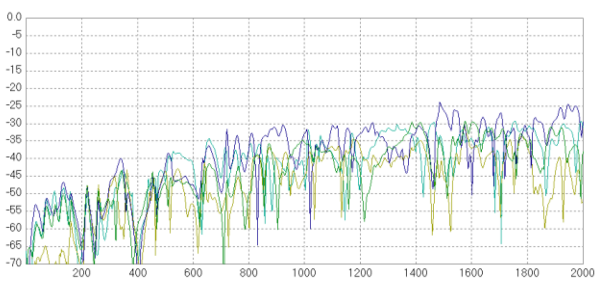


Figure 17b – Far end coupling attenuation of an unscreened Cat5e acc. to figure 13, Ssd21, lin

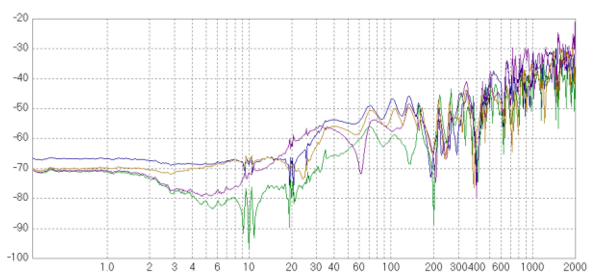


Figure 17c – Far end coupling attenuation of an unscreened Cat5e acc. to figure 13, Ssd21, log

Measurements of an unscreened Cat5e cable with triaxial set-up according to figures 13 & 16 are shown in figure 17. The screening attenuation (Ssc21) of about 10 to 15 dB can be explained by the remaining pairs which acts as inner screen. Concerning measurement uncertainties see 9.2.

The coupling attenuation (Ssc21) is about 5 to 10 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.

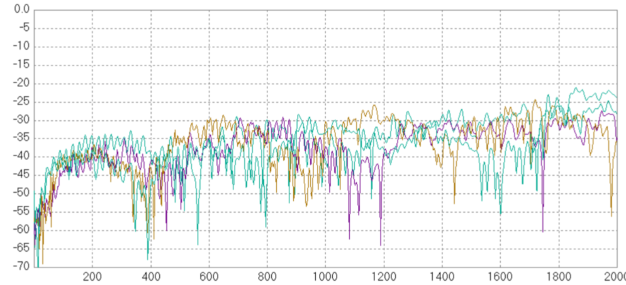


Figure 17d – Far end unbalance attenuation of an unscreened Cat5e acc. to EN 50289-1-9

5.4 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.

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.

Figure 18 –TP connecting unit for four pairs

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.

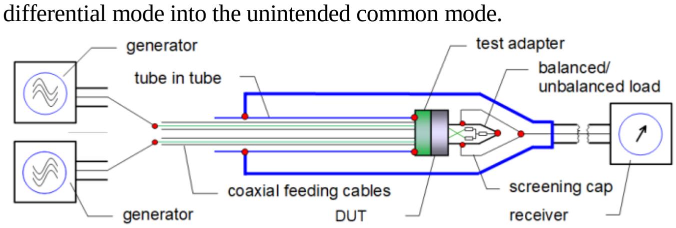


Figure 19 – Balunless a_C measurement of a balanced connector with test adapter, direct feeding, principle

The measurement of the Coupling attenuation requires a pure differential test signal and if too much conversion into the common mode occurs due to poor connection, a part of the measured result will be falsified due to screening attenuation of the DUT.

We can divide between two basic concepts when realizing differential adapters. One concept uses coaxial feeding cables reaching right to the adapter (fig. 19) having the advantage that the needed performance of coaxial feeding cables can be very well qualified or that the VNA calibration plane could be even located at the end of the coaxial feeder cables.

The second concept applies to balanced feeding cables (fig. 20). Following the second concept, market available differential cable assemblies which are showing up the required connector interface could be reworked and finished with a suitable housing to build up the test adapter. The dis-advantage is the more difficult qualification of the electrical requirements.

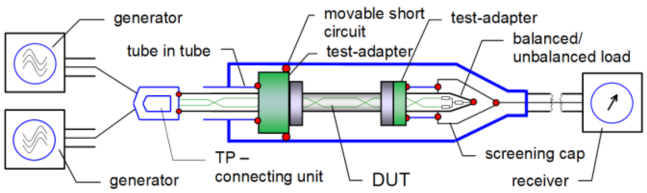


Figure 20 – Balunless measurement of coupling attenuation of a cable assembly, principle

Both concepts need to be connected to the generators delivering the test signals. This is a minor problem with the coaxial feeder cables of concept 1 where we find standard coaxial connectors.

To get the balanced feeding cables of concept 2 connected a TP-connecting unit must be applied providing the adaptation of the coaxial generator ports to a suitable differential cable contact.

Figure 21 – Near end tube connection for unscreened balanced pairs & connectors

Recently, a new TP-connection unit (fig. 18) was introduced in [18]. It is designed for connecting 4 balanced pairs and provides 360° shield contact for cable screens. It is specified for a bandwidth of 2GHz and therefore suitable for the new category 8 cables and connectors, respectively.

Table 1 – Performance of the TP-connecting unit

Characteristic impedance of the primary side (single ended)	50 Ω
Characteristic impedance of the secondary side (differential mode)	100 Ω
Return loss, differential mode	> 20 dB
Attenuation, differential mode	< 0,3 dB
Unbalance attenuation (TCTL)	> 40 dB

Since the TP-connection unit can be coupled direct to the triaxial tube with consistently ground connection (fig. 21), it is also useful for the triaxial screening- and coupling attenuation measurement of screened and unscreened balanced pairs.

5.5 Screening effectiveness at higher frequencies

Up to now the max. frequency of interest to measure screening attenuation with triaxial set-up is about 3 GHz. Different stakeholders, e.g. the automotive industry ask to measure screening attenuation also at higher frequencies.

This could be performed in principle with the basic set-up of the triaxial procedure see figure 6, but the tube becomes a circular waveguide at certain frequencies [19, 20].

With the inner diameter D of the tube and the diameter d of the DUT, the cut-off frequency for the H11-wave (TE11-wave) is given by:

$$\lambda_{g_{H11}} \approx \frac{\pi}{2}(D+d) \qquad (10)$$

which is about 4 GHz for a tube with 40 mm inner Diameter (CoMeT 40) with a RG 214 as DUT. (Λ_{gH11} is approx. 20 GHz for RG 214 itself) For the E01-wave the cut off frequency Λ_{gE01} is given by:

$$\lambda_{g_{E01}} \approx D - d \qquad (11)$$

which is about 9,3 GHz for a tube with 40 mm inner diameter (CoMeT 40) and a RG 214 as DUT.

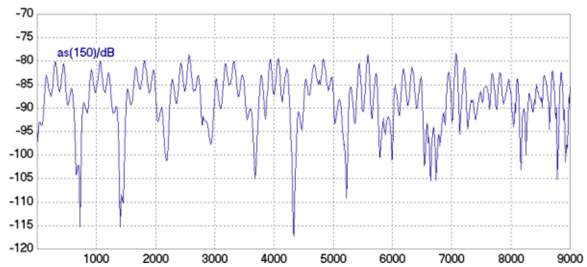


Figure 22 – Screening attenuation of a RG 214 up to 9 GHz in triaxial tube CoMeT 40

The influence of the H11 mode can be minimized if the CUT is mounted concentrically (symmetric) in the tube. Figure 22 shows the measurements of the screening attenuation of a RG 214 up to 9 GHz.

The measurement was performed with commercial available triaxial test equipment without any modification; the DUT was centered in the tube by using a foam support.

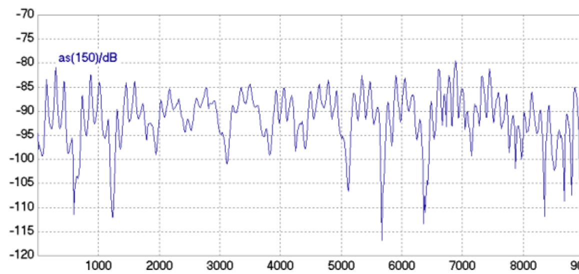


Figure 23 – Screening attenuation of a RG 214 up to 9 GHz in triaxial cell with absorber

Measurements up to 9 GHz can be performed also in the triaxial cell, see figure 23. Resonances respectively higher order modes are suppressed by magnetic absorber [20].

The influence of the position and the shape of the DUT on the test result is under further study. [21]

6. Standardisation

The first international standard for Triaxial test procedure was published in IEC 96-1Ed3:1971, Generic for coaxial cables, Subclause A5.2, transfer impedance due to resistive and magnetic coupling and Subclause A5.3, Transfer admittance due to capacitive coupling.

IEC 96-1 was replaced later by IEC 1196-1 and after that by IEC 61196-1. Since 2002 EMC test procedures of the former IEC 96-1 are now developed as standalone documents as 62153-4-n series under the scope of IEC TC 46/WG5.

Table 2 - IEC Standards for Triaxial test procedures

TS 62153-4-1 2014-01	Introduction to electromagnetic (EMC) screening measurements
62153-4-3Ed2 2013-10	Surface transfer impedance - Triaxial method
62153-4-4Ed2 2015-04	Shielded screening attenuation, test method for measuring of the screening attenuation a_S up to and above 3 GHz
62153-4-7Ed2 2015-12	Shielded screening att. test method for measuring the Transfer impedance Z_T and the screening att. a_S or the coupling att. aC of RF-Connectors and assemblies up to and above 3 GHz, Tube in tube method
62153-4-9Ed2 2018-04	Electromagnetic Compatibility (EMC) – Coupling attenuation, triaxial method
62153-4-10 Ed2 2015-11	Shielded screening attenuation test method for measuring the Screening Effectiveness of Feed troughs and Electromagnetic Gaskets
62153-4-15 2015-12, **Ed2** in preparation	Test method for measuring transfer impedance and screening attenuation - or coupling attenuation with Triaxial Cell
62153-4-16 2016-10	Relationship between surface transfer impedance and screening attenuation, Conversion a_S and Z_T

EN 50289-1-6 Electrical test methods - Electromagnetic performance - was developed parallel to the IEC test procedures by CLC TC 46X/WG 3 and published in 2002. It details four different EMC test procedures:

- Transfer impedance, triaxial method
- Transfer impedance, line injection method
- Screening attenuation test method, triaxial method
- Coupling attenuation or screening attenuation, absorbing clamp method

The procedures described herein have in principle the same content than the comparable IEC test procedures. Since all of the comparable IEC procedures were revised recently, CLC TC 46X has decided to refer only to IEC 62153-4-n standards for future projects and withdraw EN 50289-1-6.

7. Unscreened pairs with clamps

Figure 24a shows the measurement of the screening attenuation of an unscreened balanced pair with the absorbing clamp procedure according to draft IEC 62153-4-5Ed2, see figure 2.

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 taken from each position.

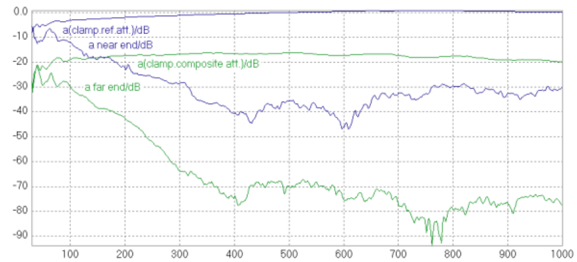


Figure 24a – Screening att. of an unscreened balanced pair with absorbing clamp MDS 21

Whereas the triaxial measurement of the screening attenuation of an unscreened pair is close to zero (fig. 14), the screening attenuation measured with MDS 21 shows much higher values towards higher frequencies.

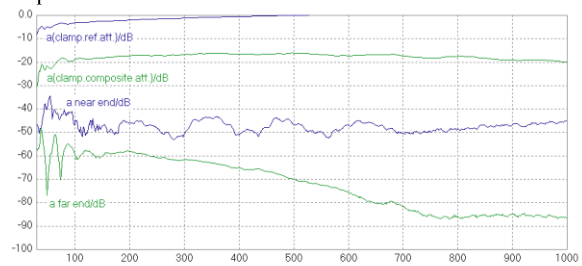


Figure 24b – Coupling att. of an unscreened balanced pair with absorbing clamp MDS 21

The measured coupling attenuation with clamp MDS 21 is shown in figure 24b. It deviates from the measured coupling attenuation with triaxial set-up as well as from the measured far and near end unbalance attenuation (fig. 12 & 15) with unexpectedly poor values below 100 MHz.

During the revision of IEC 62153-4-5, measuring of screening effectiveness of unscreened balanced pairs with absorbing clamps should be discussed with IEC TC 46/WG5. Calibration procedures and the clamp behavior, especially below 100 MHz should be considered.

8. Conclusion & outlook

The triaxial test procedure is in use for more than 80 years and is still prevailing. It covers a broad frequency range from DC up to and above 3 GHz (9 GHz) and a broad range of different test procedures for different applications and different kind of test samples. Improvements, extensions and new triaxial procedures are in progress continuously in cooperation with IEC TC 46/WG5.

EMC of screened and unscreened balanced cables below 30 MHz 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.

Test adapter for different balanced connectors and assemblies are in preparation. A new TP-connection unit was introduced.

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

Hence the triaxial test procedure should be the preferred respectively the reference procedure to measure the coupling attenuation of screened and unscreened balanced cables as already established for coaxial cables.

For single unscreened pairs, the set-up for near end coupling (fig. 11) is in principle the same than the measurement of near end unbalance (Scd11).

The set-up for the far end coupling (fig. 13) is a Ssd12 measurement, (diff. feeding and single ended measurement) which is comparable to the the far end unbalance measurement.

Consequently, and proven by the test results, the coupling attenuation of an unscreened balanced single pair is in principle its unbalance attenuation at near and far end respectively. At multiple unscreened pairs, the remaining pairs act as an "inner" screen and improves the coupling attenuation by about 10 dB.

Advantage of the triaxial procedure to measure coupling attenuation of screened and unscreened balanced pairs is the defined ground potential, the close RF-tight set-up and the broad frequency range. Only one set-up is needed.

Further triaxial measurements of coupling attenuation of unscreened balanced single and multiple TPs and comparable measurements with absorbing clamps should be performed and discussed.

9. Measurements

9.1 General

All measurements were performed at the bedea test labs with VNA R&S-ZNB 8 4-port, & R&S-ZNB 20 4-port. Full 4port VNA calibration was performed with R&S ZV-Z51 ecal-kit

Test set-ups were the bedea CoMeT system and Lüthi MD21 absorbing clamps. Matching PCBs were 50/50/25.TP-Connecting unit was the unit described under 5.4. as well as the bedea TP-Connecting unit for single pair measurement.

Triaxial measurements are raw measurements of the respective S-parameters without corrections. All graphs are in dezibels, dB and in MHz.

9.2 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 $a_{S,lf}$ (fig. 9a, 9b & 17c) 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.

10. Acknowledgments

Special thanks to Otto Breitenbach (†2003) the father of the Triaxial set-up to measure the screening attenuation of cable screens in the GHz range (fig. 3). His engagement opened the field for the development of several further triaxial test procedures at higher frequencies.

Special thanks also to Lauri Halme who was the convenor of IEC TC 46/WG5 (former 46A/WG1) from 1973 – 1993 & from 1998 – until today. He attended and developed the triaxial test procedures over more than 4 decades.

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Thomas Hähner received in 1989 his Diploma in Electrical Engineering (Dipl.-Ing. (FH)) with emphasis on Telecommunications Technology from the Georg Simon Ohm University of Applied Science in Nuremberg (Germany) and in 2000 his Diploma in Business Administration (Dipl. Wirt.-Ing. (FH)) from the University of Applied Science in Wildau (Germany). Thomas Hähner is in the cable business since 1990 where he joined Nexans in Nuremberg (Germany) as an R&D engineer of radio frequency and data transmission cables and manager of the RF test laboratory. Today he is still with Nexans and since September 2015 Technical Manager for Aerospace-Defense-Medical based in Paris area (France).

He is active since more than 20 years in standardization committees. In 2010, Thomas Hähner was granted for the 1906 IEC Award in recognition of his outstanding technical contribution in developing, writing and finalizing TC 46's IEC 62153-4 series (Metallic communication cable test methods - Electromagnetic compatibility). Thomas is Chairman of IEC technical committee TC46 (Cables, wires, waveguides, R.F. connectors, R.F. and microwave passive components and accessories) and Chairman of CENELEC technical committee TC46X (Communication Cables).

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Thomas Schmid received his apprenticeship diploma as Telecommunications Technician in 1989 and his Dipl.-Ing. (FH) degree in Electrical Engineering with emphasis on Telecommunications Technology from the Munich University of Applied Sciences in 1996.

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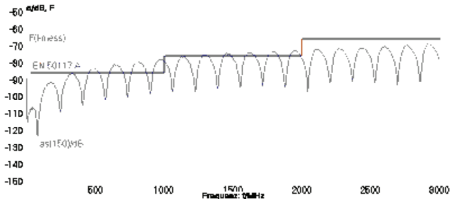
Thomas Schmid is participating in international standardisation since 2006. He is member of different commitees and working groups of the IEC TC 46 family.

Thomas Schmid was granted for the 1906 IEC Award in recognition of his outstanding technical contribution in developing, writing and finalizing TC 46's IEC 62153-4 series (Metallic communication cable test methods - Electromagnetic compatibility).

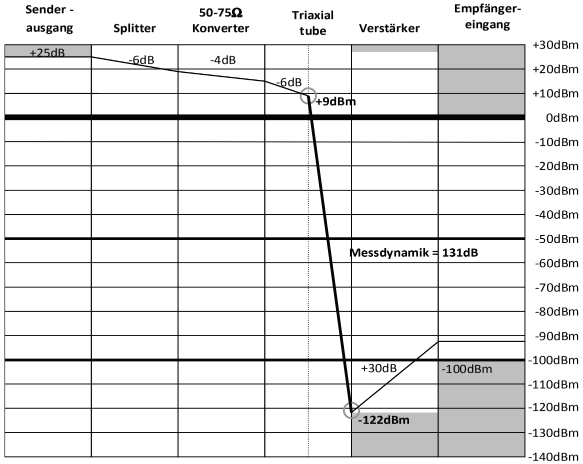
All authors are active members of IEC TC 46/WG5, Test methods and limits for the electromagnetic compatibility (EMC) of metallic cables and other passive components, by the measurement of their electromagnetic coupling with the environment.

Test system- CoMeT - Measurement accuracy and reproducibility in EMC measurements of cables and connectors with Triaxial test procedure

calibration respectively normalisation unit



estimation of available dynamic



$$L_R = -174dBm + NF + 10\log(S_F)dB + 10\log\left(\frac{B_{ZF}}{Hz}\right)dB$$

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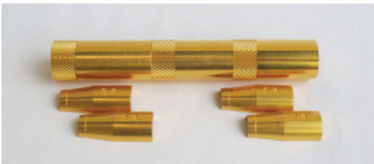

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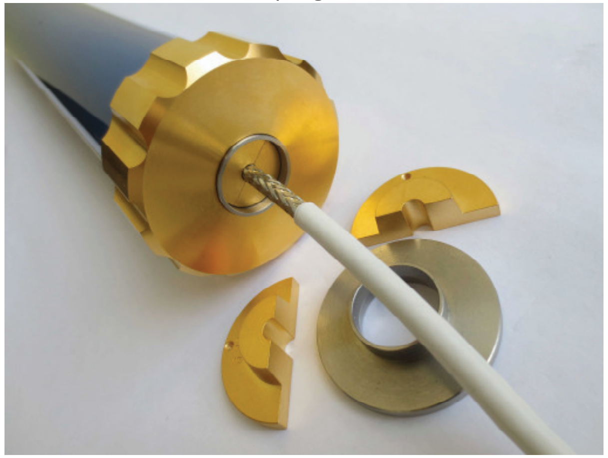

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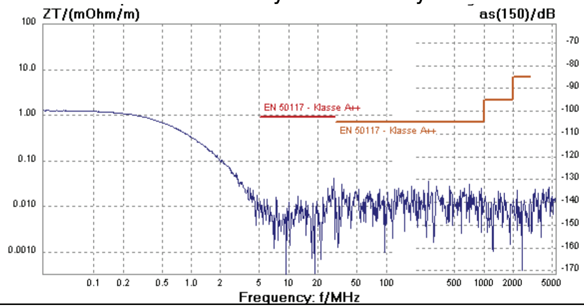

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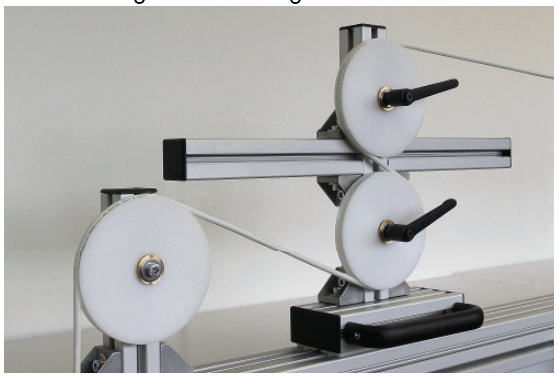

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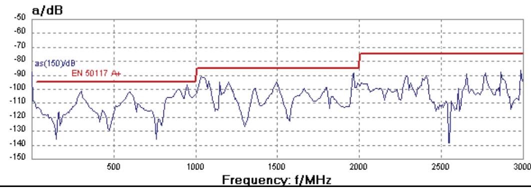

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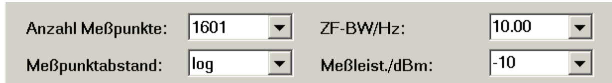
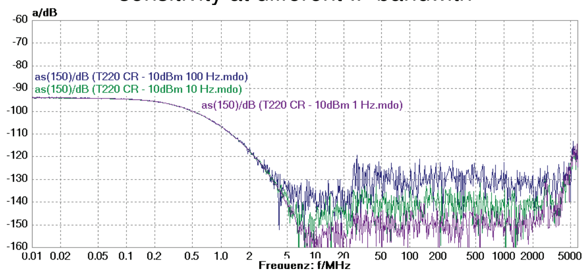
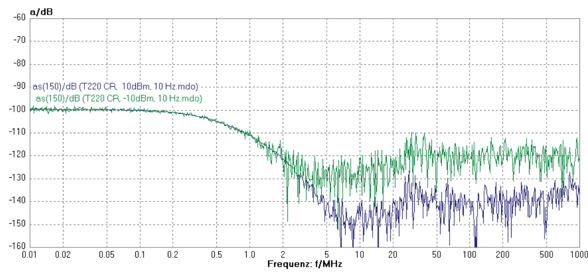


sensitivity at different IF bandwith

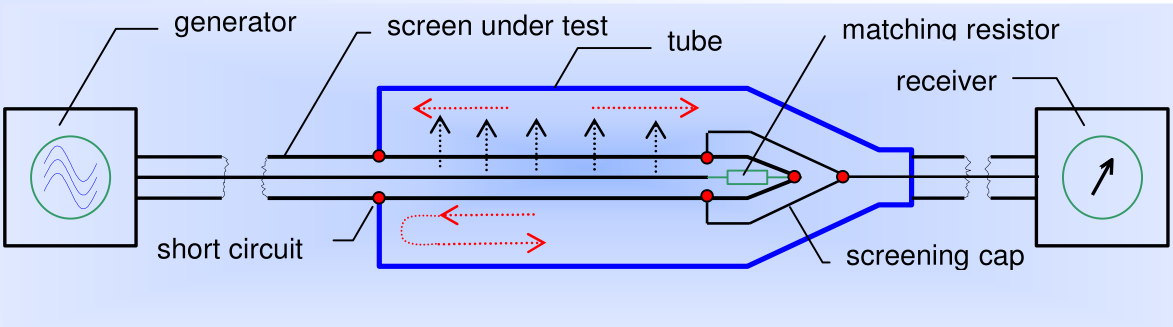


sensitivity at different power levels -10 dBm / 10 dBm

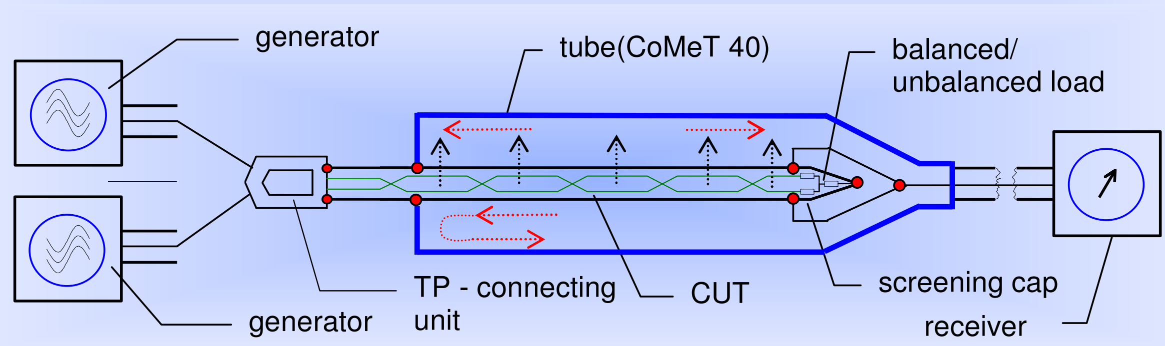


Test-system CoMeT, bda connectivity GmbH, Herborner Strasse 61a, 35614 Asslar, Germany +49 6441 384 5255, bernhard.mund@bda-c.com

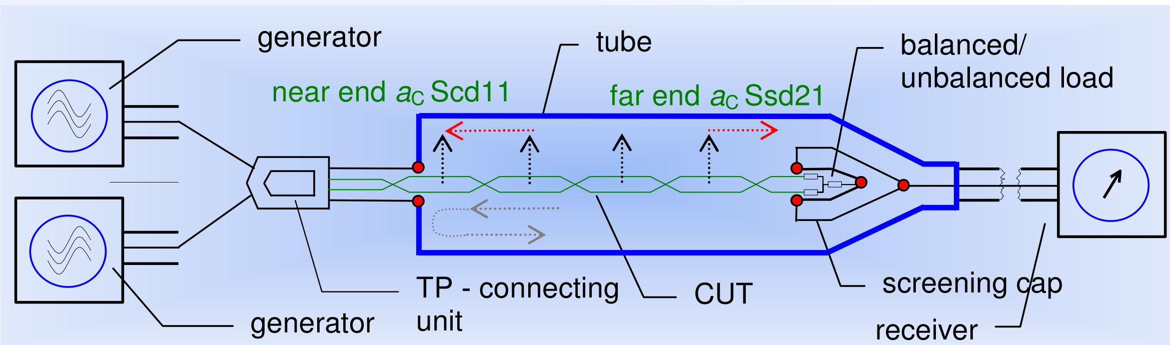
Screening effectiveness of unscreened balanced pairs



IEC 62153-4-3/ -4Ed2, Transfer impedance & Screening attenuation



IEC 62153-4-9Ed2, Coupling attenuation a_C – Triaxial method



IEC 62153-4-9Ed2Amd1 Coupling attenuation a_C of unscreened balanced pairs

TP-Connecting unit for CoMeT system

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