TECHNICAL REPORT

IEC 61917

First edition
1998-06

Cables, cable assemblies and connectors – Introduction to electromagnetic (EMC) screening measurements

Câbles, cordons et connecteurs – Introduction aux mesures de blindage électromagnétique

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TECHNICAL REPORT – TYPE 3

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Câbles, cordons et connecteurs –
Introduction aux mesures de blindage électromagnétique

International Electrotechnical Commission 3, rue de Varembé Geneva, Switzerland
Telefax: +41 22 919 0300 e-mail: inmail@iec.ch IEC web site http: //www.iec.ch

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

CABLES, CABLE ASSEMBLIES AND CONNECTORS – INTRODUCTION TO ELECTROMAGNETIC (EMC) SCREENING MEASUREMENTS

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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- type 2, when the subject is still under technical development or where, for any other reason, there is the future but not immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard, for example “state of the art”.

Technical reports of types 1 and 2 are subject to review within three years of publication to decide whether they can be transformed into International Standards. Technical reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

IEC 61917 which is a technical report type 3 has been prepared by subcommittee 46A: Coaxial cables, of IEC technical committee 46: Cables, wires, waveguides, r.f. connectors, and accessories for communication and signalling.

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

Committee draft	Report on voting
46A/267/CDV	46A/284/RVC

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

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

CABLES, CABLE ASSEMBLIES AND CONNECTORS – INTRODUCTION TO ELECTROMAGNETIC (EMC) SCREENING MEASUREMENTS

1 Scope and object

Screening (or shielding) is one basic way of achieving electromagnetic compatibility (EMC). However, a confusingly large number of methods and concepts is available to test for the screening quality of cables and related components, and for defining their quality. This technical report gives a brief introduction to basic concepts and terms trying to reveal the common features of apparently different test methods. It should assist in correct interpretation of test data, and in the better understanding of screening (or shielding) and related specifications and standards.

2 Reference documents

IEC 60096-1:1986, *Radio-frequency cables – Part 1: General requirements and measuring methods*
Amendment 2 (1993)

IEC 60096-2:1961, *Radio-frequency cables – Part 2: Relevant cable specifications*
Amendment 1 (1990)

IEC 60096-4-1:1990, *Radio-frequency cables – Part 4: Specification for superscreened cables – Section 1: General requirements and test methods*

IEC 60169-1:1987, *Radio-frequency connectors – Part 1: General requirements and measuring methods*

IEC 60169-1-3:1988, *Radio frequency connectors – Part 1: General requirements and measuring methods – Section 3: Electrical tests and measuring procedures – Screening effectiveness*

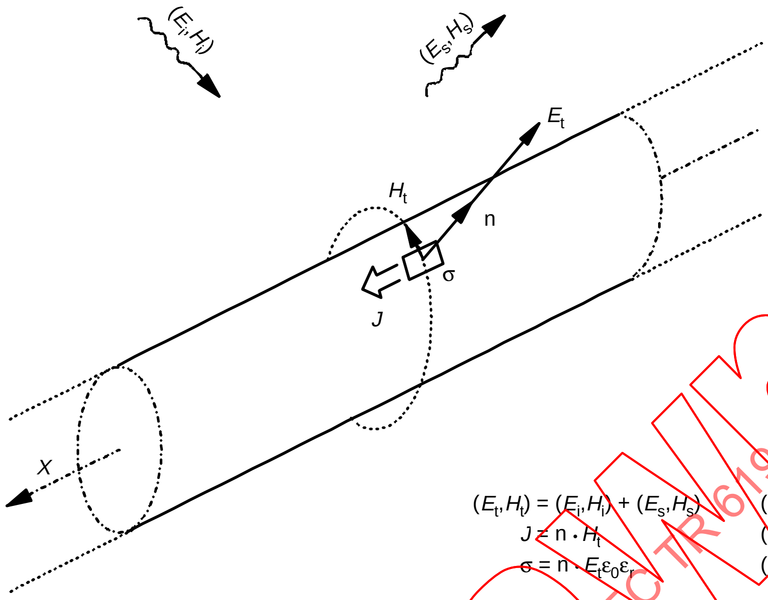
IEC 61196-1:1995, *Radio-frequency cables – Part 1: Generic specification – General, definitions, requirements and test methods*

IEC 61726:1995, *Cable assemblies, cables, connectors and passive microwave components – Screening attenuation measurement by the reverberation chamber method*

3 Electromagnetic phenomena

It is assumed that if an electromagnetic field is incident on a screened cable, there is only weak coupling between the external field and that inside, and that the cable diameter is very small compared with both the cable length and the wavelength of the incident field. The superposition of the external incident field and the field scattered by the cable yields the total electromagnetic field (E_t, H_t, in figure 1). The total field at the screen's surface may be considered as the source of the coupling: electric field penetrates through apertures by *electric* or capacitive coupling; also magnetic fields penetrate through apertures by *inductive* or magnetic coupling.

Additionally, the induced current in the screen results in *conductive* or resistive coupling.

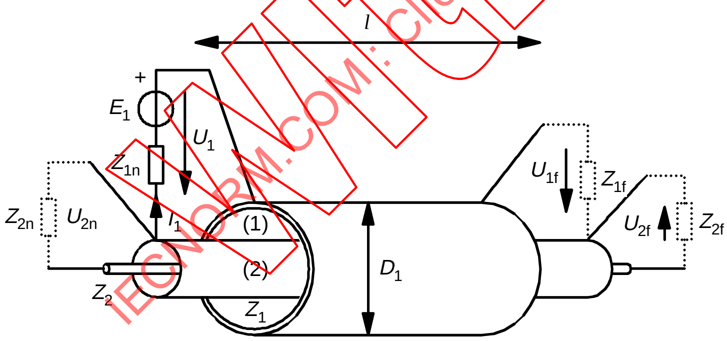


$$(E_t,H_t) = (E_i,H_i) + (E_s,H_s) \quad (1)$$
$$J = n \cdot H_t \quad (2)$$
$$\sigma = n \cdot E_t \varepsilon_0 \varepsilon_r \quad (3)$$

n: unit vector normal to surface

Figure 1 – Incident (i), scattered (s) and resulting total electromagnetic fields (E_t, H_t) with induced surface current- and surface charge-densities J (A/m) and σ (C/m²)

As the field at the surface of the screen is directly related to density of surface current and surface charge, the coupling may be assigned either to the total field (E_t, H_t) or to the surface current- and charge- densities (J and σ). Consequently, we may simulate the coupling into the cable by reproducing through any means the surface currents and charges on the screen. Because we assume a cable of a small diameter, we may neglect higher modes and can use an additional coaxial conductor as our injection structure, as shown in figure 2.



Concept of a triaxial set-up

1) outer circuit, formed by injection cylinder and screen, characteristic impedance Z_1,

2) inner circuit, formed by a screen, and centre conductor, characteristic impedance Z_2; screening at the ends not shown.

Observe the conditions Z_{1f}, Z_{2n}, Z_{2f} and λ in figure 3a and figure 3b.

NOTE 1 – $D_1 << l$.

NOTE 2 – Both ends of circuit (2) must be well screened.

Figure 2 – Defining and measuring screening parameters – A triaxial set-up

4 The intrinsic screening parameters of short cables

The *intrinsic parameters* refer to an infinitesimal length of cable, like the inductance or capacitance per unit length of transmission lines. Assuming *electrically short cables*, with $l << \lambda$ which will always apply at low frequencies, the intrinsic screening parameters are defined and can be measured as follows:

4.1 Surface transfer impedance, Z_T

As shown in figure 2 and figure 3a (where Z_{1f} and Z_{2f} are zero):

$$Z_T = U_2 / (I_1 \cdot l) \qquad (\Omega / \mathrm{m}) \tag{4}$$

The dependence of Z_T on frequency is not simple and is often shown by plotting log Z_T against log frequency. Note that the phase of Z_T may have any value, depending on braid construction and frequency range.

NOTE – In circuit 2 of figure 3a the voltmeter and short circuit can be interchanged.

4.2 Capacitive coupling admittance, Y_c

As shown in figure 2 and figure 3b (where Z_{1f} and Z_{2f} are open circuit):

$$Y_C = \mathrm{j}\omega C_T = I_2 / (U_1 \cdot l) \qquad (\mathrm{mho} / \mathrm{m}) \tag{5}$$

The through capacitance (C_T) is a real capacitance and has usually a constant value up to 1 GHz and higher (with aperture $a << \lambda$).

While Z_T is independent of the characteristics of the coaxial circuits, C_T is dependent on those characteristics. There are two ways of overcoming this dependence:

a) The *normalized through elastance* K_T derived from C_T is independent of the size of the outer coaxial circuit, but it depends on its permittivity:

$$K_T = C_T / (C_1 \cdot C_2) \qquad (\mathrm{m} / \mathrm{F}) \qquad K_T \sim 1 / (\varepsilon_{r1} + \varepsilon_{r2}) \qquad (6)\ (7)$$

where C_1 and C_2 are the capacitance per unit length of the two coaxial circuits.

b) The *capacitive coupling impedance* Z_F again derived from C_T is also independent of the size of the outer coaxial circuit and, for practical values of ε_{r1}, is only slightly dependent on its permittivity:

$$Z_F = Z_1 Z_2 Y_C = Z_1 Z_2\, \mathrm{j}\omega C_T \quad (\Omega / \mathrm{m}) \quad Z_F \sim \sqrt{(\varepsilon_{r1} \cdot \varepsilon_{r2})} / (\varepsilon_{r1} + \varepsilon_{r2}) \qquad (8)\ (9)$$

Compared with Z_T, Z_F is usually negligible, except for open weave braids. It may, however, be significant when Z_{2n} and $Z_{2f} >> Z_2$ (audio circuits).

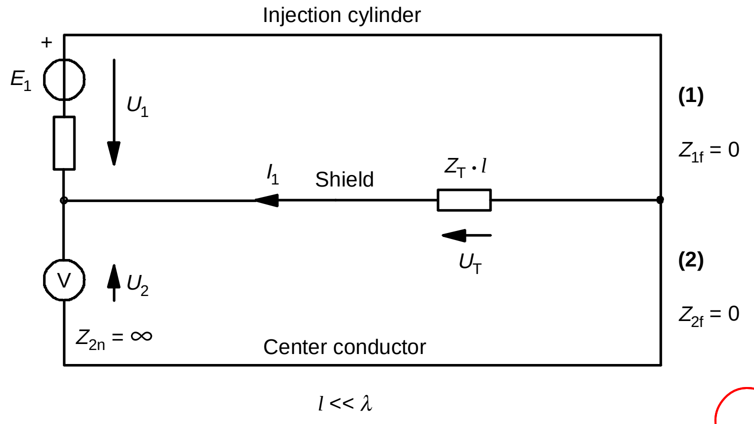


Figure 3a – Equivalent circuit for the definition and possible testing of Z_T

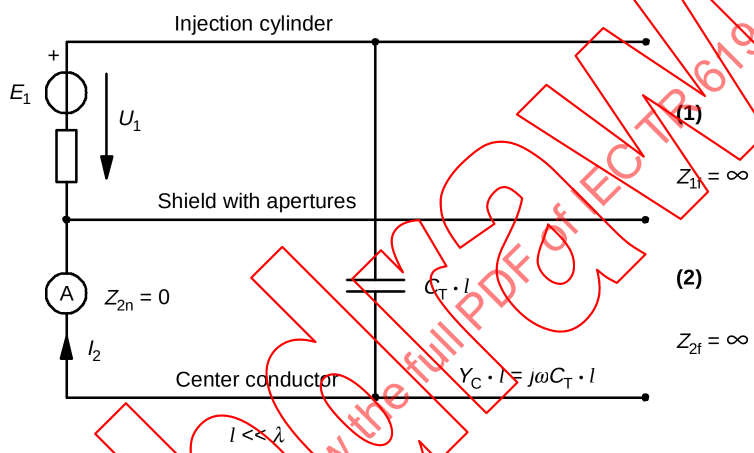
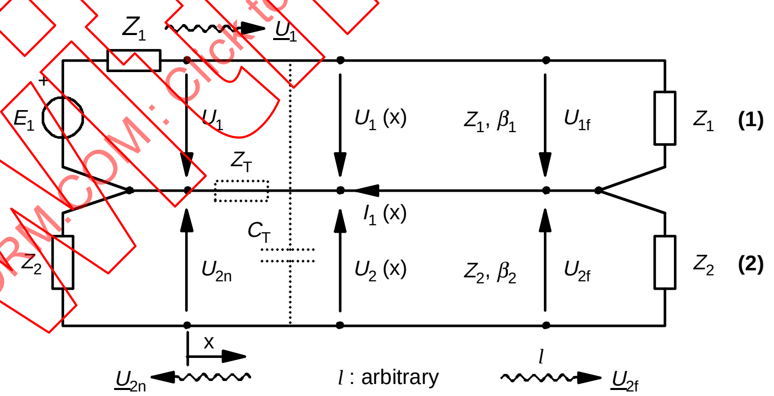


Figure 3b – Equivalent circuit for the definition and possible testing of $Y_C = j\,\omega C_T$



NOTE – Z_T and C_T are distributed (not correctly shown here). The loads Z_2 at the ends may represent matched receivers.

Figure 3c – Definition of electrical quantities in a set-up that is matched at all ends

Figure 3 – Defining and measuring screen parameters – Equivalent circuits

4.3 Injecting with arbitrary cross-sections

A coaxial outer circuit has been assumed so far in this report, but it is not essential because of the invariance of Z_T and Z_F. Using a wire in place of the outer cylinder, the injection circuit becomes two-wire with the return via the screen of the cable under test. Obviously the charge and current distribution become non-uniform, but the results are equivalent to coaxial injection, especially if two injection lines are used opposite to each other, and may be justified for worst-case testing. Note that the IEC *line injection test* uses a wire.

4.4 Reciprocity and symmetry

Assuming linear shield materials, the measured Z_T and Z_F values will not change when interchanging injection (1) and measuring (2) circuits. Each of the two conductors of the two-line circuit can be interchanged, but in practice the set-up will have to take into account possible ground loops and coupling to the environment.

4.5 Arbitrary load conditions

When the circuit ends of figure 3a and figure 3b are not ideally short or open circuit, Z_T and Z_F will act simultaneously. The superposition is noticeable in the low frequency coupling of the matched circuits (figure 3c and table 1).

5 Long cables – coupled transmission lines

The coupling over the whole length of the cable is obtained by summing up (integrating) the infinitesimal coupling contributions along the cable while observing the correct phase. It is expedient to make the following assumptions and conventions:

– matched circuits considered with the voltage waves $\underline{U}_1$, $\underline{U}_{2n}$, $\underline{U}_{2f}$, see figure 3c,

– representation of the coupling, using the normalized wave amplitudes $U/\sqrt{Z}\left[\sqrt{Watt}\right]$, instead of voltage waves, i.e. the *coupling transfer function*, in the following denoted by "*coupling function*", will be defined as

$$T_n = \frac{\underline{U}_{2n} / \sqrt{Z_2}}{\underline{U}_1 / \sqrt{Z_1}} \quad , \qquad T_f = \frac{\underline{U}_{2f} / \sqrt{Z_2}}{\underline{U}_1 / \sqrt{Z_1}} \qquad (10)\ (11)$$

NOTE 1 – $\left|T\right|^2$ is the ratio of the power waves travelling in circuits **(2)** and **(1)**. Due to reciprocity and assuming linear screen (shield) materials, *T* is reciprocal, i.e. invariant with respect to the interchange of injection and measuring circuits (1) and (2).

NOTE 2 – The quantity $\left|1/T\right|^2$, or in logarithmic quantities

$$A_S = -20 \log_{10} \left|T\right|, \qquad (12)$$

may be considered as the "screening attenuation" of the cable, specific to the set-up.

Performing the straight forward calculations of coupled transmission line theory, the coupling function *T*, given in table 1, is obtained. The term $S\{l\,f\}$ is the *"summing function" S*, being dependent on l and *f*. (The wavy bracket just indicates that the product $l \cdot f$ is the argument of the function *S* and not a factor to *S*). *S* represents the phase effect, when summing up the infinitesimal couplings along the line, and is:

$$S_{\substack{n\\f}}\{l\,f\} = \frac{\sin\dfrac{\beta l \pm}{2}}{\dfrac{\beta l \pm}{2}} \exp\left\{-\,j\,\frac{\beta l +}{2}\right\} \qquad (13)$$

with

$$\beta l \pm = (\beta_2 \pm \beta_1)\cdot l = 2\pi l\, f\,\{1/v_2 \pm 1/v_1\} \\ = 2\pi l\, f\,(\sqrt{\varepsilon_{r2}} \pm \sqrt{\varepsilon_{r1}})/c \qquad \text{(14a) (14b) (14c)}$$

subscript ± refers to near/far end respectively

+ refers to both near/far ends

Note that weak coupling, i.e. $T \ll 1$, has been assumed. This case, including losses, is given in [20 Halme, Szentkuti]* .

NOTE – The equation (15) and representation in table 1 visualizes the contributions of the different parameters to the coupling function T:

$$T_{\substack{n\\f}} = (Z_F \pm Z_T)\cdot\frac{1}{\sqrt{Z_1\cdot Z_2}}\cdot\frac{l}{2}\cdot S_{\substack{n\\f}}\{l\cdot f, \varepsilon_{r1}, \varepsilon_{r2}\} \qquad (15)$$

Note especially the following points:

a) There may be a directional effect ($T_n \neq T_f$) in the whole frequency range if Z_F is not negligible. (But Z_F is usually negligible except with loose, single braid shields.)

b) Up to a constant factor, T is the quantity directly measured in a set-up.

c) For low frequencies, i.e. for short cables ($l \ll \lambda$), the trivial coupling formula is obtained that is directly proportional to l :

$$T_{\substack{n\\f}} = (Z_F \pm Z_T)\cdot\frac{1}{Z_{12}}\cdot\frac{l}{2}; \quad \text{with} \quad Z_{12} = \sqrt{Z_1\cdot Z_2} \qquad \text{(16a) (16b)}$$

d) The summing function $S\{l\cdot f\}$ is presented in figure 4. Note also that:

e) $S\{l\cdot f\}$ has a sin(x)/x behaviour. A cut-off point may be defined as $(l\cdot f)_C$:

$$(l\cdot f)_{C_{\substack{n\\f}}} = \frac{c}{\pi\left|\sqrt{\varepsilon_{r1}} \pm \sqrt{\varepsilon_{r2}}\right|} \qquad (17)$$

f) The exact envelope of $S\{l\cdot f\}$ is

$$\mathrm{Env}\left|S_{\substack{n\\f}}\{l\cdot f\}\right| = \frac{1}{\sqrt{1+\dfrac{(l\cdot f)^2}{(l\cdot f)^2_{\substack{cn\\f}}}}} \qquad (18)$$

* Numbers in square brackets refer to the bibliography (see annex B).

Table 1 – The coupling transfer function *T* (coupling function)[1)]

Set-up parameters [2)]

$$(Z_1), l, \varepsilon_{r1}$$

$$T_{\substack{n\\f}} = (Z_F \pm Z_T)\cdot \frac{1}{\sqrt{Z_1 \cdot Z_2}} \cdot \frac{l}{2} \cdot S_{\substack{n\\f}}\{l\cdot f, \varepsilon_{r1}, \varepsilon_{r2}\}$$

Intrinsic
screen parameters

Cable parameters [2)]
$(Z_2, l), \varepsilon_{r2}$

"Low-frequency coupling",
short cables [3)]

"HF-effect",
cut-off $(l\cdot f)_C$.

Length + frequency effect

---

1) T^2 is the power coupling from circuit (1) to circuit (2).

The stacked subscripts $\substack{n\\f}$ are associated to the stacked operation symbols ± in the obvious way: upper subscript → upper operation, lower subscript → lower operation.

2) ε_{r1} and ε_{r2} contained in *S* as parameters.

3) for $l << \lambda$: $S\{l\cdot f\} \to 1$.

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g) The first minimum (zero) of $S\{l\cdot f\}$ occurs at

$$(l\cdot f)_{\min} = \pi\,(l\cdot f)_C . \qquad (19)$$

h) As seen from equations (13) and (18), below the cut-off points $(l\cdot f)_{\substack{cn\\f}}$ is $S\{l\cdot f\} \approx 1$ and above them it starts to oscillate and its envelope drops asymptotically 20 dB/decade,

$$\mathrm{Env}\left| S_{\substack{n\\f}}\{l\cdot f\} \right| \approx \frac{\left((l\cdot f)_{\substack{cn\\f}}\right)}{(l\cdot f)} \qquad (20)$$

i) S is symmetrical in l and f, i.e. l and f are interchangeable. For a fixed length a cut-off frequency f_c and vice versa, for a fixed frequency a cut-off length l_c may be defined. Substituting c/λ_o for f, we obtain the cut-off length as

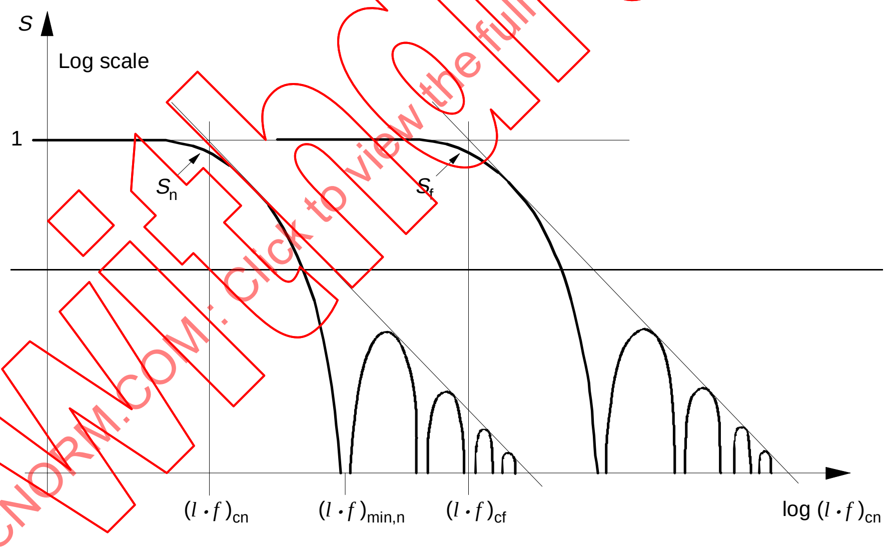
$$l_{C_{n \atop f}} = \frac{\lambda_o}{\pi \left| \sqrt{\varepsilon_{r1}} \pm \sqrt{\varepsilon_{r2}} \right|} \tag{21}$$

j) The effect of S in the frequency range (l = constant) is illustrated in figure 5. The coupling function is proportional to Z_T, only if $f < f_c$. Note also the typical values indicated for f_c.

k) The minima and maxima of S are not resonances, they are due to cancelling and additive effects of the coupling along the line.

l) The far end cut-off frequency is significantly influenced by the permittivity of the outer system (ε_{r1}). Selecting $\varepsilon_{r1} \rightarrow \varepsilon_{r2}$ we obtain $(l \cdot f)_{Cf} \rightarrow \infty$, i.e. no cut-off at the far end. Due to practical aspects (tolerances, homogeneity, etc.), an ideal phase matching $(\varepsilon_{r1} \equiv \varepsilon_{r2})$ is not feasible.

m) The total effect of l on the coupling is not contained in S alone, but in the product $l \cdot S\{l \cdot f\}$. The product $l \cdot S$ is presented in figure 7 for f = constant. The coupling function T which can be measured in a set-up, is proportional to l if $l < l_C$. However, for appropriately long cables $(l > l_C)$, the maximum coupling is independent of l and we obtain a length independent shielding attenuation above the cut-off point $(l \cdot f)_C$. But we should remember that $(l \cdot f)_C$ as well as A_s are still dependent on the set-up parameters (ε_{r1}, Z_1) .



NOTE – $S_f > S_n$ above near end cut-off, yielding a directive effect.

$(l \cdot f)_C$: cut-off point

Figure 4 – The summing function $S\{l \cdot f\}$ for near (n) and far (f) end coupling

$$Z_T\left(f_1 = 10\ \text{MHz}\right) = 20\ \ \text{m}\Omega\,/\,\text{m}$$

Figure 5a – Transfer impedance of a typical single braid screen

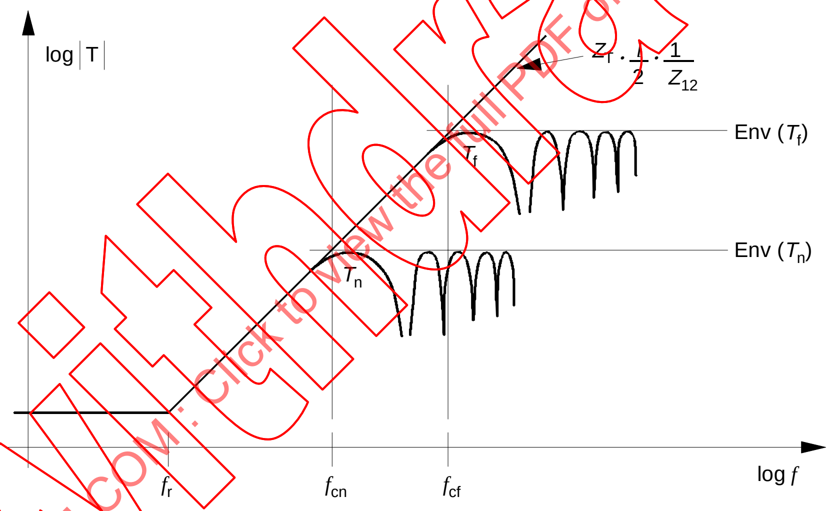


Figure 5b – Coupling transfer function for the same cable with negligible Z_F $\left(Z_F \ll Z_T\right)$: frequency responses of figure 4 and figure 5a added on log scale

Note the cut-off effect for $f > f_c$.

Example: $\varepsilon_{r1} = 1$ (set-up), $\varepsilon_{r2} = 2.2$ (cable),

$l = 1\ \text{m} \qquad \rightarrow f_{Cn} = 40\ \ \text{MHz}, \quad f_{Cf} = 200\ \ \text{MHz}$

Figure 5 – The effect of the summing function

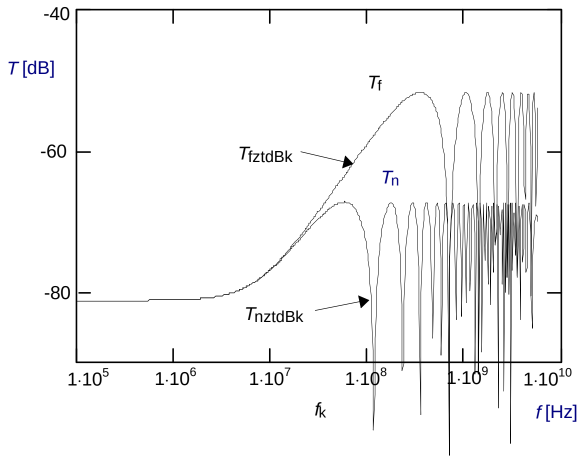


Figure 6a – Calculated coupling transfer functions T_n and T_f for a single braided when Z_F = 0

– In calculations the used parameters are:

Z_T (d.c.) =15 mΩ/m and Z_T (10 MHz) = 20 mΩ/m increasing 20 dB/decade (see figure 5a), cable length 1 m, and velocities of the outer and inner line: v_1 = 200 Mm/s and v_2 = 280 Mm/s corresponding a velocity difference of 40 %.

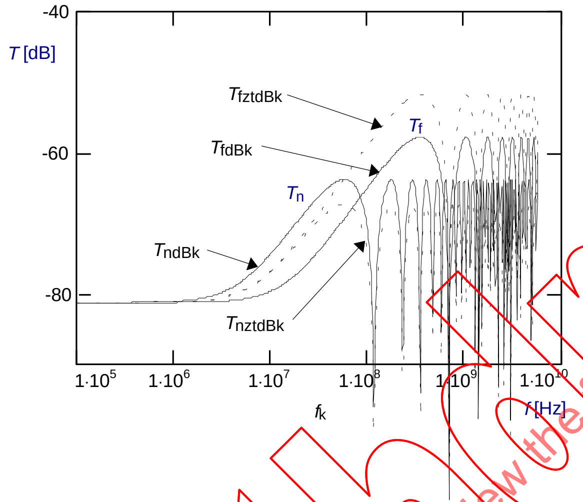


Figure 6b – As figure 6a but Im(Z_T) is positive and Z_F = +0,5*Im (Z_T) at high frequencies:

– T_n is 3,5 dB higher and T_f 6 dB lower than in reference figure 6a because

$T_n \sim |Z_F + Z_T|$ = 1,5*Z_T and

$T_f \sim |Z_F - Z_T|$ = 0,5*Z_T .

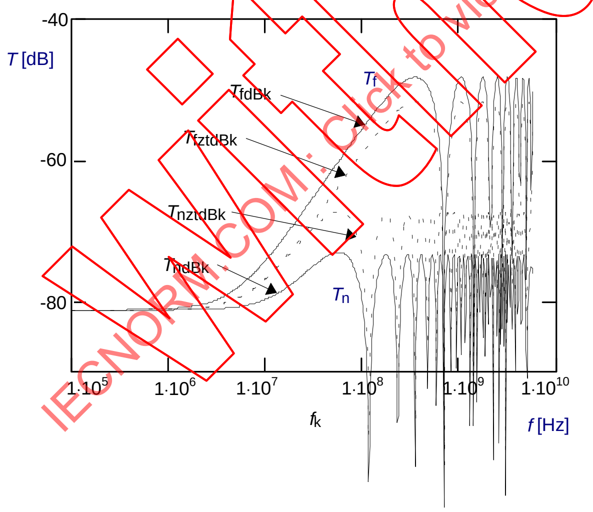


Figure 6c – As figure 6a but Im(Z_T) is negative and Z_F = –0,5*Im(Z_T) at high frequencies:

– T_f is 3,5 dB higher and T_n 6 dB lower than in reference figure 6a because

$T_f \sim |Z_F - Z_T|$ = 1,5* $|Z_T|$ and

$T_n \sim |Z_F + Z_T|$ = 0,5* $|Z_T|$

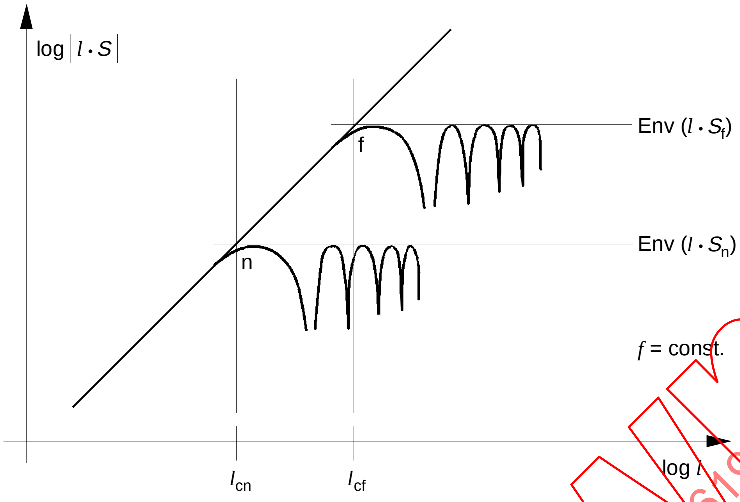
NOTE 1 – T_n for near-end, T_f for far-end and dB means that $T_{n,f}$ are calculated in dB (20 lg | $T_{n,f}$ |)

NOTE 2 – T_n dB: near-end when $Z_F = (1/2) \cdot Z_T$ and T_{nzt} dB: near-end when Z_F = 0.

NOTE 3 – T_f dB: far-end when $Z_F = (1/2) \cdot Z_T$ and T_{fzt} dB: far-end when Z_F = 0.

Figure 6 – The effects of the Z_T and Z_F to the coupling transfer functions T_n and T_f

– In figure 6a, Z_F = 0.
– In figure 6b and figure 6c, Z_F is significant ($Z_F = (1/2) \cdot Z_T$).
– In figure 6b Z_T is positive and figure 6c negative at high frequencies.



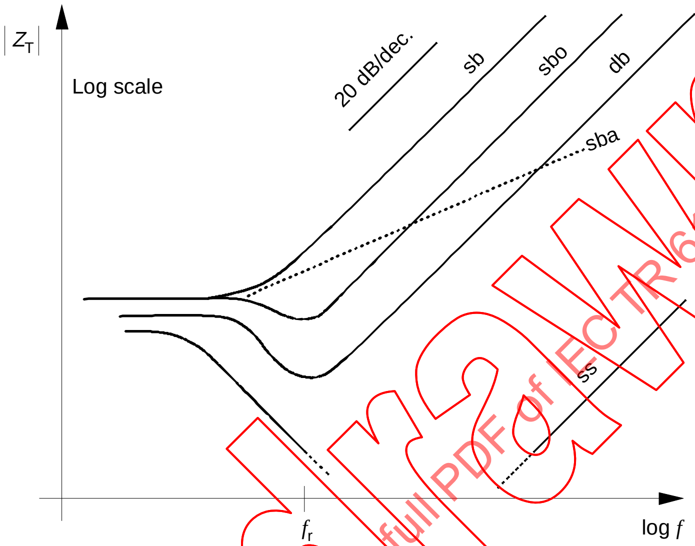
NOTE 1 – For $l > l_C$, the maximum value of *T* is attained, i.e. the maximum coupling (or the screening attenuation) is not dependent on l .

NOTE 2 – l_{Cf} strongly depends on ε_{r1} .

Figure 7 – $l \cdot S$: the complete length dependent factor in the coupling function *T* (see table 1)

6 Transfer impedance of a braided-wire outer conductor or screen

Typical transfer impedances of cables with braided-wire screens are shown in figure 8. The constant Z_T value at the low-frequency end is equal to the DC resistance of the screen, the 20 dB/decade rise at the high-frequency end is due to the inductive coupling through the screen and the dip at the middle frequencies is caused by eddy currents or skin effect of the braid. Some braided cables may behave anomalously having less than a 20 dB/decade rise at high frequencies. By using an extrapolation of 20 dB/decade we are in most cases on the conservative side. This extrapolation can be used up to several GHz.



where

f_r: typically 1...10 MHz

sb: single braid

sbo: single braid optimized

sba: single braid 'anomalous'

db: double braid

ss: superscreen

Figure 8 – Transfer impedances of typical cables

An electrically short piece of braided coaxial cable (2) is considered to be placed in a triaxial arrangement as in figure 2.

It is assumed that the outer circuit (1) is the disturbing one. As stated a braided cable has a transfer impedance Z_T that increases proportionally to frequency at high frequencies, because of the leakage of the magnetic field through holes in the braid.

The total flux of the magnetic field induced by the disturbing current I_1 is Φ_1. A part of it, Φ'_{12} leaks directly through the holes and includes a disturbing voltage U'_2 in the inner circuit. However, a part Φ''_{12} of Φ_1 flows in the braid and complicates the mechanism of the total magnetic leakage by the following additional phenomenon:

The braiding wires alternate between the outer and inner layer. It means that the inner and outer braid wires are likewise ingredients of both the inner (1) and outer (2) circuit of figure 9a.

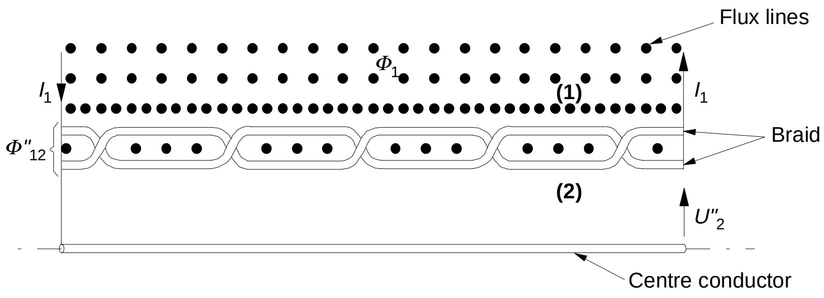


Figure 9a – Complete flux

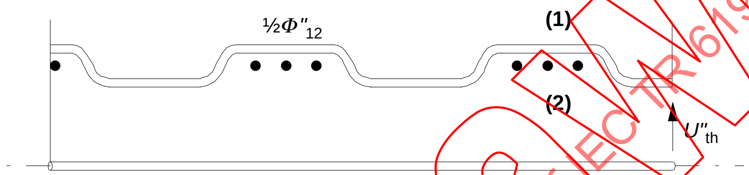


Figure 9b – Left-hand lay contribution

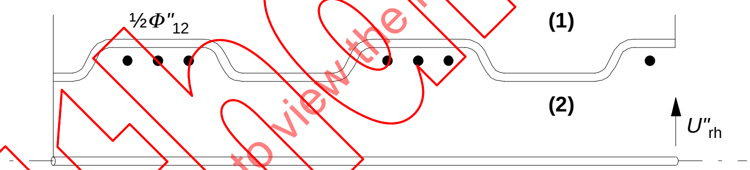


Figure 9c – Right-hand lay contribution

Figure 9 – Magnetic coupling in the braid

Therefore it is necessary and unavoidable that Φ''_{12} is partly also in the inner circuit, figure 9b. Both the right hand (rh) and left hand (lh) lay of the braiding wires bring into the inner circuit (2) an equal disturbing voltage U''_2 induced by Φ''_{12} / 2. The voltages are in parallel:

$$U''_{rh} = U''_{lh} = U''_2 = ½\mathrm{j}\omega\Phi''_{12} \tag{21}$$

This phenomenon is similar to the "magnetic part" of the coupling through a homogeneous screen.

The two induced disturbing voltages oppose each other.

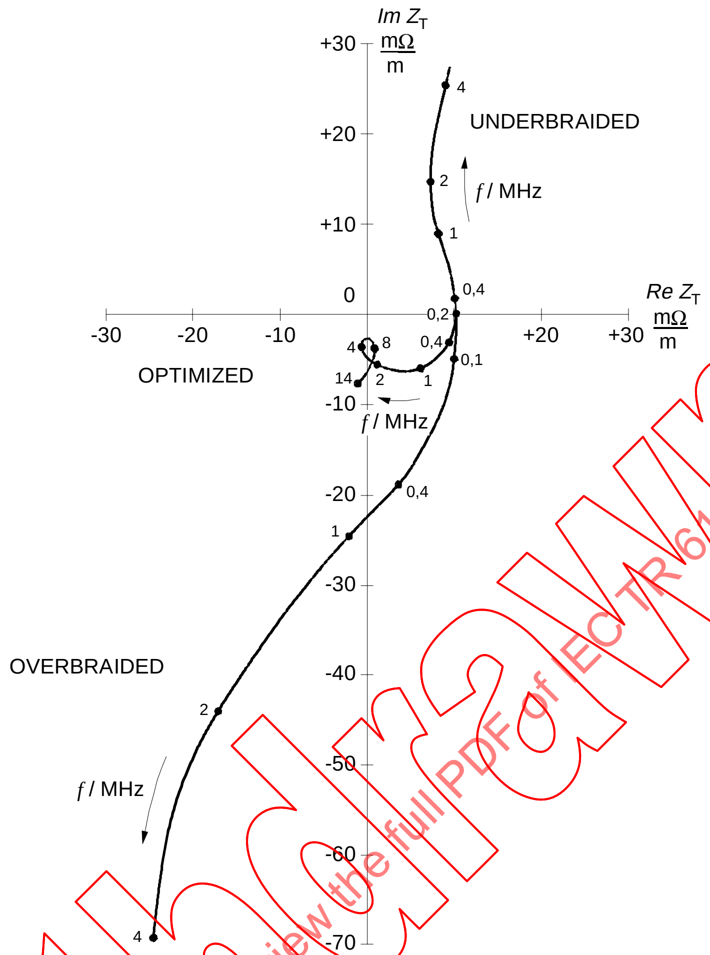


Figure 10a – Complex plane, Z_T = Re Z_T + j Im Z_T, frequency f as parameter

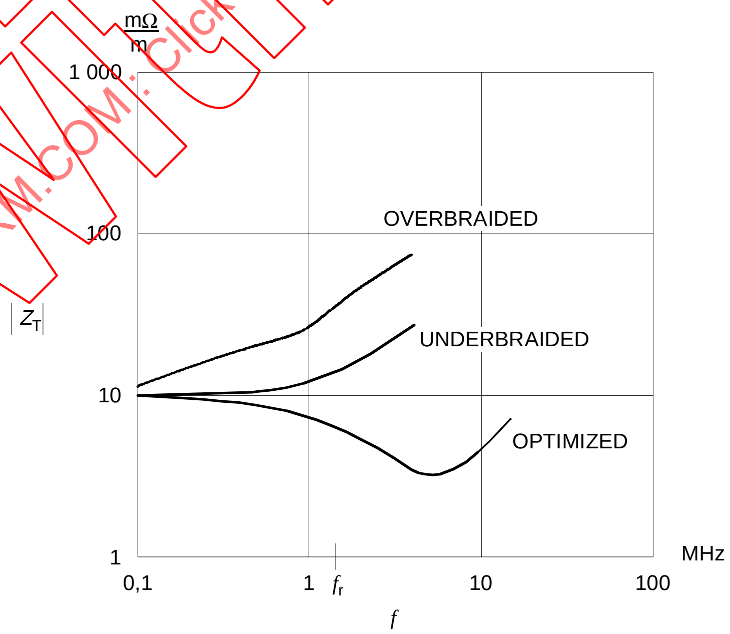


Figure 10b – Magnitude (amplitude), | Z_T (f) |

Figure 10 – Measured transfer impedance Z_T (d.c. resistance Z_T (d.c.) is set to the value of 10 mΩ/m)

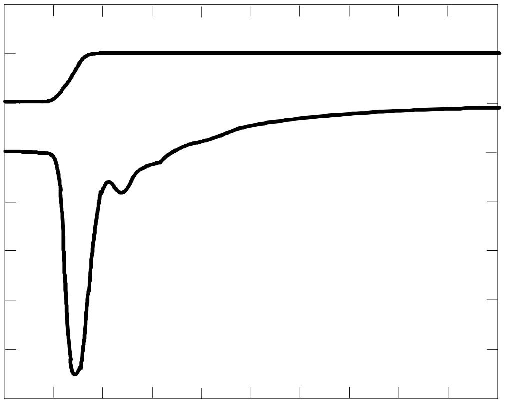


Figure 11a – Overbraided cable

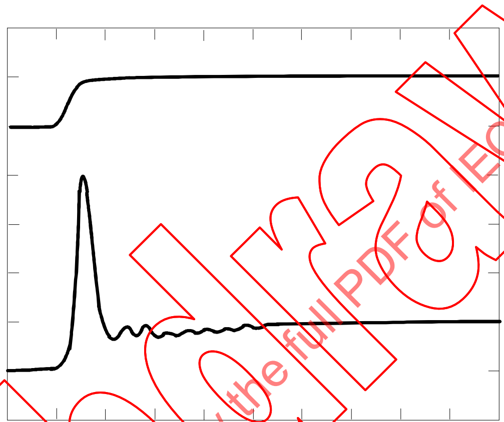


Figure 11b – Underbraided cable

Top trace: Injection step current (100 mA/div)

Time base: 50 ns/div

Amplifier gain: 30 dB, therefore Z_T (time) = 12,5 mΩ/m/div

Lower trace: The height of the spike corresponds to –

Figure 11a – Z_T (3 MHz) = –4,7 × 12,5 mΩ/m = –59 mΩ/m

Figure 11b – Z_T (3 MHz) = +4 × 12,5 mΩ/m = +50 mΩ/m

Figure 11 – Typical Z_T (time) step response of an overbraided and underbraided single braided outer conductor of a coaxial cable

Braid optimization is based on these important physical facts. Both leakage phenomena can be described by mutual inductances:

$$M'_{12} = \frac{\Phi'_{12}}{j\omega I_1} \tag{22}$$

$$M''_{12} = \frac{1}{2} \cdot \frac{\Phi''_{12}}{j\omega I_1} \tag{23}$$

Clearly it is possible to make braided-wire screens where either M'_{12} or M''_{12} are dominant or where they cancel each other, Therefore, underbraided, overbraided or optimized braids may be considered. Figure 10a shows measured transfer impedances in the complex plane of such screens and the main transfer impedance components of a braided screen can be observed. From the optimized case it can be concluded that at low frequencies the braid behaves approximately as a homogeneous tubular screen. The same can be concluded from figure 10b where the transfer impedance amplitudes are shown as a function of frequency, but from figure 10b it cannot be seen directly if the screen is underbraided or overbraided.

The transfer impedance of a braided-wire screen consists of the three above-mentioned main components:

(i) At low and medium frequencies the tubular screen coupling behaviour (Z_{Th}) varies with eddy currents and decreasing Z_T. In [14 Vance] it is stated that a good approximation for Z_{Th} is a tubular homogeneous screen [5 Schelkunoff] with the thickness of one wire diameter and the same d.c. resistance as the braid.

(ii) The mutual inductance M'_{12} is related to direct leakage of the magnetic flux Φ'_{12}.

(iii) The mutual inductance M''_{12} (negative) is related to the magnetic flux Φ''_{12} in the braid.

By adding these components a good approximation is obtained for the transfer impedance Z_T of a braided-wire screen

$$Z_T \approx Z_{Th} + \mathrm{j}\,\omega\,(M'_{12} - M''_{12}) \qquad (24)$$

and the first approximation of the equivalent circuit is shown in figure 12a.

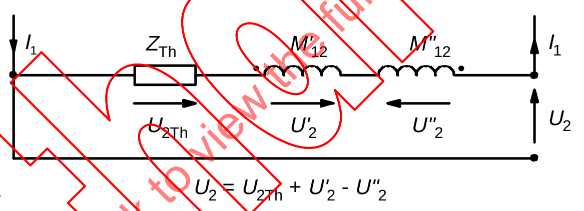


Figure 12a – Contributions to the transfer impedance

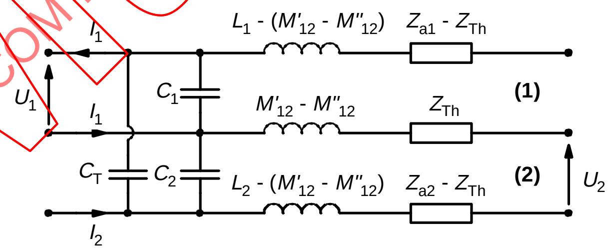


Figure 12b – Significant elements of circuits (1) and (2)

Figure 12 – Z_T equivalent circuits of a braided-wire screen

A more complete equivalent circuit where the through capacitance C_T and surface impedances Z_a of the braided cable are incorporated is shown in figure 12b. L_1 and L_2 are the (external) inductances of the outer and inner circuit.

Many attempts have been made to calculate the transfer impedance of a braided coaxial cable. Most of the literature [15 Ikrath], [2 Kaden], [14 Vance] have concentrated on models of braided screens and calculation of direct leakage of the magnetic field induced by I_1, and of M'_{12}. Satisfactory results have been achieved.

There exists very little literature [1 Fowler], [3 Tyni] on M''_{12} but the matter has been studied by IEC SC 46A/WG 1 and its successor TC 46/WG 5. Especially the calculation and stability of M''_{12} have been shown to be very problematic because of so many uncertain and unstable parameters, e.g. the resistance of the crossover points of the wires, which have an effect on the magnetic field distribution in the braid. Also the pressure of the jacket has an effect on the small space between the right hand lay and left-hand lay of the braided wires. Not to mention the number of wire ends per carrier and the braid angle and the tightness and optical coverage of the braid.

After understanding the magnetic coupling mechanisms it is not surprising that the transfer impedances of braided-wire screens vary considerably and are unstable for many braid and cable constructions whether or not they are optimized. It is also clear that a perforated tube cannot be used as a model for a braided screen.

It is clear that a loose highly optimized braid can have a very unstable Z_T during bending, twisting and/or pressing. An overbraided screen with a high filling factor or optical cover normally has a (pure) negative transfer impedance at high frequencies because of a large M''_{12} coupling through the mutual "space" between the left and right lays of the braid in comparison with a small leakage through the braid M'_{12}. Pressure on the jacket would improve the screening performance by diminishing the mutual "space" and decrease the Z_T.

The manufacture of a good stable optimized cable requires the control of braid parameters such as:

– braid angle, tension (and lubricant) of the strands;
– number of strand in a spindle;
– wire diameter;
– plating:
– pressure on the braid;
  – in manufacturing;
  – of the jacket.

IEC TC 46/WG 5, Screening effectiveness, is studying the impact of these parameters on an optimized braid when preparing a guide for braided optimization based on theory and practice.

A guide on screening optimization of braids will help the IEC family to talk the same language when setting limits for electromagnetic screening parameters (Z_T; Z_F; a_s) of braided cables.

7 Test possibilities

A number of test procedures are used to test cables for their screening properties, some of which will be found in IEC standards. Each procedure has benefits for some users which for historical reasons may not be widely appreciated. Table 2 summarizes the test procedures available, some of which will be discussed here, with special reference to their applicability to cables, cable assemblies and connectors.

7.1 Measuring the transfer impedance of coaxial cables

All tests listed in table 2 can be used on coaxial cables, but if a single test is needed to cover frequencies above and below 100 MHz, tests 1, 4, 7, 9 and 10 can be dismissed. Of the others, those with 's' under 'grouping' (column 3) have better intrinsic isolation between measuring and injection circuits, while in those with 'o' under grouping the injection circuit is unscreened. The difference is the line interchange referred to in section 4.4 above. One benefit of an unscreened injection line is that better access may be obtained for inspection of the cable under test, which may be useful if the sample is in any way flawed. The two test methods with unscreened injection lines are 3 and 8. The latter, with its wide frequency coverage is recommended for future testing.

7.2 Measuring the transfer impedance of cable assemblies

Even with a restricted frequency range, many of the tests listed in table 2 are not suited to tests on cable assemblies. Tests 1, 4, and 6 are unsuitable because an electrically short sample may be needed to achieve the upper frequencies, while test 10 is still limited to frequencies above 100 MHz. Tests with screened injection wires (2 and 5) are difficult to set up due to the varying cross section of the assembly, a difficulty which also applies to test 3. Such objections leave tests 7, 8 and 9. To set against its low (effective) upper frequency limit, with test 7 it is easy to distinguish between connector and cable contributions, so it is ideal in a diagnostic role. Test 9 works only above 30 MHz, which may be restrictive. Test 8 will require several measurements on each sample, as it is unreasonable to assume that a cable assembly has circular symmetry.

It is only fair to state that in any frequency domain test on cable assemblies where signal phase is not recorded, a test is only valid if the sample length is not varied (tests carried out on a sample of one length, cannot be used to assess a sample of another length – whether it be longer or shorter). Of the transfer impedance tests being discussed, only test 7 can be used in this way.

Multi-conductor cable assemblies are more complex, because the 'core' cannot be considered to be coaxial. A test for such cable assemblies has not yet been addressed.

7.3 Measuring the transfer impedance of connectors

In principle, all the tests in table 2 can be used on coaxial connectors.

As with tests on cable assemblies, there is much benefit to be gained from using a test with an unscreened injection circuit, though other tests will remain in the standard, because they have become accepted. If it is possible to distinguish the screening of a connector from that of the attached cable, this will considerably ease the test procedure.

Multi-pin connectors are far more numerous and varied than coaxial connectors. However, non-circular connectors cannot be tested by the means implied by the test procedures of table 2, though by suitable variation test 7 and test 10 would become appropriate. *This problem is under study.*

NOTE – These methods give only an outline for measurement of symmetrical multicore cables, multipin connectors and cable assemblies made with these components.

The problems to address come from:

a) the fact that a connector is electrically short, while the parameters of a cable are distributed, and it may be electrically long;

b) multi-core cables rarely have circular symmetry. This applies both physically and to the signal paths on their conductors;

c) most multi-pin connectors have no circular symmetry; nor are they equally spaced from other conductors, which might couple to them;

d) economics will dictate that a cable assembly test should apply to other assemblies using the same components, even though of differing overall length.

Table 2 – Screening effectiveness of cable test methods for surface transfer impedance Z_T

Short title	Reference	Grouping (note 1)	Frequency range		Injection N or F (note 2)	Advantages or shortcomings
			Possible	Actually used		
1 IEC triaxial	Fig. A9 of IEC 60096-1 Fig. 44 of IEC 61196-1	kf s	d.c. – 50 MHz	10 kHz – 30 MHz	F	Rigid test rig
2 Terminated triaxial (Simons)	Fig. A5 of IEC 60096-1	m s	10 kHz – 1 GHz	100 kHz – 500 MHz	N F	Flexible test jig relies on ferrites
3 Braid injection (Fowler)	AESS(TRG)71181 [6]	m o	d.c. – 500 MHz	10 kHz – 500 MHz	N F	Flexible test needs good screening on measuring system
4 Quadraxial	[7]	m s	100 kHz – 50 MHz	100 kHz – 1 GHz	N	Deep resonances make use above 50 MHz theoretically impossible. The test has been used for assessing screening at frequencies up to 1 GHz
5 Matched T triaxial (Staegar)	IEC 60169-1-3 [8] [9]	m s	1 kHz – 12 GHz	100 MHz – 10 GHz 10 kHz – 100 MHz	N F	Rigid test jig needs good screening
6 ERA triaxial (Smithers)	[10]	kf s	d.c. – 400 MHz	10 kHz – 300 MHz	F	Very short CUT requires amplifier or phase locked loop
7 Line injection (time domain)	IEC 60096-4-1 [11]	m o	d.c. – 100 MHz	1 kHz – 80 MHz (note 3)	N F	Very easy to use. Needs good screening in measuring amplifier
8 Line injection (frequency domain)	Figures 34 and 35 of IEC 61196-1 [4] [12]	m o	d.c. – 20 GHz	10 kHz – 3 GHz	N F	Flexible and cheap measuring set-up, equipment needs to be well shielded
9 Open screening attenuation test method (absorbing clamp)	Figures 50 to 52 of IEC 61196-1	m o	30 MHz – 2,5 GHz	30 MHz – 1 GHz 300 MHz – 2,5 GHz	N F	Poor sensitivity. Measuring of a_s is dependent on the surroundings
10 Reverberation chamber method	IEC 61726 [13]	kn kf	0,1 GHz →	0,3 GHz – 40 GHz	N & F	Flexible in use, but a complex and expensive computer controller with sophisticated test software needed
11 Shielded screening attenuation test method	[16] [17] (note 4)	m s	d.c. – 5 GHz	10 kHz – 3 GHz	F	High-sensitivity measurements can be made without a screened room
12 Open multipin connector screening test method	[18] [19]	o	d.c. – 1 GHz	10 kHz – 700 MHz	N	Low cost and flexible