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(ACCESS TRANSMISSION SYSTEMS ON METALLIC CABLES)

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Cable reference models for simulating metallic access networks

This is a living document, to be updated every ETSI meeting, when new input arises

Author	Rob F.M. van den Brink	tel:	+31 70 3325389
	KPN Research,	fax:	+31 70 3326477
	PO Box 421	email:	R.F.M.vandenBrink@research.kpn.com
	2260 AK Leidschendam		
	The Netherlands		

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PART 1 - *generic modelling*

PART 2 - *operator specific data*

PART 1 - *generic modelling*

1. Scope and objective

The scope of this technical report is to provide a reference that reviews cable models on metallic, unshielded, access network wire pairs. These cables are standard telephony lines, used in various countries. The objective is to enable reliable simulations on the transmission of very high bit-rate digital signals, including ISDN, ADSL, HDSL, VDSL and any future xDSL variant, up to 52Mb/s. The cable models have been published by various European Telcos/PTTs, and include transmission, reflection and crosstalk aspects.

2. Formal description of cable transfer

The aim of this paragraph is to define naming and notation conventions and to relate various quantities dealing with cables. This paragraph is restricted to lineair cable descriptions in the frequency domain. The word *parameter* will refer to a frequency dependent quantity, and *constant* to a frequency independent quantity. The letter 'x' refers to the cable length, and symbols such as γ_x refers to a cable parameter for a given length 'x'. When the index 'x' is omitted, the symbol refers to a cable parameter per unit length (in meters or sometimes in kilometers), or a cable parameter that is (nearly) independent from the cable length. The default unit length in this document is the meter (m), to follow SI-conventions, and sometimes the kilometer (km). Note that in ANSI models sometimes a unit length is given in feet (ft) or kilofeet (kft)[1].

2.1. Two-port cable parameters

A pair of two complex parameters enable a full linear description of (reversal) symmetrical cables. The primary cable parameters $\{Z_{sx}, Y_{px}\}$, the secondary cable parameters $\{\gamma_x, Z_0\}$, and several other cable parameter pairs can be used as basic parameters to express the two-port matrix parameters.
Primary parameters have the advantage that when the frequency goes to zero, $\{Z_{sx}, Y_{px}\}$ remain finite, while the secondairy parameter Z_0 goes to very high values (or to infinity when Y_{px} becomes zero). This is an advantage when models are based on primary parameters. On the other hand, all cable and two-port parameters can uniquely be expressed in terms of secondairy parameters. This unambiguity does not hold for parameters, such as the open and short circuit impedances $\{Z_{ocx}, Z_{scx}\}$ the characteristic transmission and reflection $\{s_{Tx}, s_R\}$, or to some extend the primary parameters $\{Z_{sx}, Y_{px}\}$. This is because roots, logarithms and inverse trigonometric functions have no unique solution by nature but by *convention*.
Table 1 summarizes the relations[2] between various cable parameters.

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[1] Some English and American measures:
1 inch = 25.4 mm
1 foot = 0.3048 m = 12 inches
1 yard = 0.9144 m = 3 feet
1 statute mile = 1609.3 m = 1760 yards = 5280 feet
1 nautic mile = 1834.9 m = 2010 yards = 6020 feet (*not in use for cable dimensions*)
n AWG = $a \cdot 2^{-n/6 \cdot b}$ inch (a≈0.32486 *inch* ≈8.2514 *mm*; b≈1.00363) (American Wire Gauge, B&S, @20°C)
(⇒ 24 AWG ≈ 0.5106 mm, 26 AWG ≈ 0.4049 mm, 36 AWG = 0.005 inch, "0000"=–3 AWG=0.46 inch)

[2]
$\sinh(\gamma) = ½\cdot(\exp(\gamma) - \exp(-\gamma))$
$\cosh(\gamma) = ½\cdot(\exp(\gamma) + \exp(-\gamma))$
$\tanh(\gamma) = \sinh(\gamma)/\cosh(\gamma)$

Cable parameters (symmetrical)		
analysis	*synthesis*	*remarks*
$Z_{sx} = \gamma_x \cdot Z_0$ $Y_{px} = \gamma_x / Z_0$	$\gamma_x = \sqrt{Z_{sx} \cdot Y_{px}}$ $Z_0 = \sqrt{Z_{sx} / Y_{px}}$	primary cable parameters (series impedance and shunt-admittance)
$Z_{ocx} = Z_0 / tanh(\gamma_x)$ $Z_{scx} = Z_0 \cdot tanh(\gamma_x)$	$\gamma_x = arctanh(\sqrt{Z_{scx} / Z_{ocx}})$ $Z_0 = \sqrt{Z_{ocx} \cdot Z_{scx}}$	input impedance at open or short-circuited output of a cable, having length *x*.
$s_{Tx} = exp(-\gamma_x)$ $s_R = (Z_0 - R_N) / (Z_0 + R_N)$	$\gamma_x = -ln(s_{Tx})$ $Z_0 = R_N \cdot (1+s_R) / (1-s_R)$	characteristic transmission and reflection, normalized to reference impedance R_N

***Table 1**: Relations beween various two-port cable parameters*

In the case of a perfectly homogeneous cable along its length, the two-port is perfectly symmetrical and $\gamma_x = \gamma \cdot x$ is proportional to the cable length *x*. The same hold for $Z_{sx} = Z_s \cdot x$ and $Y_{px} = Y_p \cdot x$.
Primary and secondary parameters are sometimes divided in their real and imaginairy parts. These (real) parameters are defined in table 2. The default suffix of α_x is in this document the Neper[3] (Np), and for β_x the radian[4] (rad). Similarly are Np/m and rad/m the default suffices for α and β itselves.

$\alpha_x = real(\gamma_x)$ $\beta_x = imag(\gamma_x)$	$R_{sx} = real(Z_{sx})$ $L_{sx} = imag(Z_{sx} / \omega)$	$G_{px} = real(Y_{px})$ $C_{px} = imag(Y_{px} / \omega)$

***Table 2**: Definition of real and imaginary parts of cable parameters*

2.2. Two-port matrix parameters

A pair of secondairy cable parameters $\{\gamma_x, Z_0\}$, enable an unambiguous calculation of symmetrical two-port matrix parameters. In the case that the cable is not perfectly (reversal) symmetrical, an additional third cable parameter (q) is required[5]. In the case of a perfectly homogeneous cable, the two-port is symmetrical, so q=1, and $\gamma_x = \gamma \cdot x$ is proportional to the cable length *x*. Table 3 and 4 summarize the associated expressions for voltage, current and wave representations. They include wave representations for the cases that the characteristic transmission and reflection $\{s_{Tx}, s_R\}$ are known.
The (wave) scattering and transfer parameters (s- and t- parameters) are normalized to an arbitrary chosen (real) *reference* impedance R_N. In the case of HDSL or VDSL transmission, the preferred value is $R_N = 135\Omega$ to match the ETSI design impedances of these modems.
An adequate definition on matrix parameters is beyond the scope of this document. Detailed information on waves and scattering parameters, especially what occurs when scattering parameters are normalized

[3] The parameter α_x is in fact dimensionless, like any ratio number expressed in dB or %, The dB is not a suitable suffix, but this does not hold if it is transformed into a 'loss' quantity. The characteristic loss magnitude $|1/S_{Tx}| = exp(\alpha_x)$ can be expressed in dB by evaluating $p_x = 20 \cdot {}^{10}log(|1/S_{Tx}|) \approx 8.6859 \cdot \alpha_x$. The factor 8.6859, or more precisely 20/ln(10), illustrates why the dB is not a suitable suffix, so the Neper has took its place. Saying that α_x equals "p_x"[dB] is therefore impure language for meaning: $\alpha_x = p_x / 8.6859$ [Np]. Be aware of this confusion.

[4] The characteristic loss phase $\angle(1/S_{Tx})$ in radians equals β_x because $1/S_{Tx} = exp(\alpha_x + j \cdot \beta_x)$. Since it is not common to express a loss phase in radians, the loss phase $\angle(1/S_{Tx})$ in degrees equals $(180/\pi) \cdot \beta_x$. Saying that β_x equals "q_x" degrees is therefore impure language for meaning $\beta_x = (\pi/180) \cdot q_x$. Be aware of this confusion.

[5] In a symmetrical cable, the two image imedances Z_{01} and Z_{02} are equal, and equal to the characteristic impedance Z_0. In a non-symmetrical cable, $Z_{01} = Z_0 \cdot q$ and $Z_{02} = Z_0 / q$. Image impedances are characterized by the property that when port 2 is terminated with Z_{01} then the input impedance at port 1 is also equal to Z_{01}. The same applies for Z_{02} in the oposite direction.

to complex reference impedances, can be found in [1,2] and further in many microwave textbooks or [3].

two-port matrix parameters (symmetrical, q=1)
$\mathbf{Z} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} = \begin{bmatrix} Z_0 / \tanh(\gamma_x) & Z_0 / \sinh(\gamma_x) \\ Z_0 / \sinh(\gamma_x) & Z_0 / \tanh(\gamma_x) \end{bmatrix}$
$\mathbf{Y} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \begin{bmatrix} +1 / (\tanh(\gamma_x) \cdot Z_0) & -1 / (\sinh(\gamma_x) \cdot Z_0) \\ -1 / (\sinh(\gamma_x) \cdot Z_0) & +1 / (\tanh(\gamma_x) \cdot Z_0) \end{bmatrix}$
$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \frac{1}{(Z_0/R_n+R_n/Z_0)\cdot\tanh(\gamma_x)+2} \times \begin{bmatrix} (Z_0/R_n-R_n/Z_0)\cdot\tanh(\gamma_x) & 2 / \cosh(\gamma_x) \\ 2 / \cosh(\gamma_x) & (Z_0/R_n-R_n/Z_0)\cdot\tanh(\gamma_x) \end{bmatrix}$
$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma_x) & Z_0 \cdot \sinh(\gamma_x) \\ \sinh(\gamma_x) / Z_0 & \cosh(\gamma_x) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$
$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \begin{bmatrix} (Z_0/R_n+R_n/Z_0)/2\cdot\sinh(\gamma_x) + \cosh(\gamma_x) & (R_n/Z_0-Z_0/R_n)/2\cdot\sinh(\gamma_x) \\ (Z_0/R_n-Z_n/Z_0)/2\cdot\sinh(\gamma_x) & -(Z_0/R_n+R_n/Z_0)/2\cdot\sinh(\gamma_x) + \cosh(\gamma_x) \end{bmatrix}$
two-port matrix parameters, related to waves (symmetrical, q=1)
$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \frac{1}{1-(s_R\cdot s_{Tx})^2} \times \begin{bmatrix} s_R\cdot(1-s_{Tx}^2) & s_{Tx}\cdot(1-s_R^2) \\ s_{Tx}\cdot(1-s_R^2) & s_R\cdot(1-s_{Tx}^2) \end{bmatrix}$
$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \frac{1}{1-s_R^2} \times \begin{bmatrix} 1/s_{Tx}-s_R^2\cdot s_{Tx} & s_R\cdot s_{Tx} - s_R/s_{Tx} \\ s_R/s_{Tx} - s_R\cdot s_{Tx} & s_{Tx}-s_R^2/s_{Tx} \end{bmatrix}$

***Table 3**: Expressions for matrix parameters of symmetric cables*

two-port matrix parameters (asymmetrical q¹1)

elementary matrix parameters

$$\mathbf{Z} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} = Z_0 \times \begin{bmatrix} q / \tanh(\gamma_x) & 1 / \sinh(\gamma_x) \\ 1 / \sinh(\gamma_x) & 1/q / \tanh(\gamma_x) \end{bmatrix}$$

$$\mathbf{Y} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \frac{1}{Z_0} \times \begin{bmatrix} 1/q / \tanh(\gamma_x) & -1 / \sinh(\gamma_x) \\ -1 / \sinh(\gamma_x) & q / \tanh(\gamma_x) \end{bmatrix}$$

$$\mathbf{S} = \frac{1}{(Z_0/R_n+R_n/Z_0)\cdot\tanh(\gamma_x) + (q+1/q)} \times \begin{bmatrix} (Z_0/R_n-R_n/Z_0)\cdot\tanh(\gamma_x) + (q-1/q) & 2 / \cosh(\gamma_x) \\ 2 / \cosh(\gamma_x) & (Z_0/R_n-R_n/Z_0)\cdot\tanh(\gamma_x) - (q-1/q) \end{bmatrix}$$

cascade matrix parameters

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} \cosh(\gamma_x)\cdot q & \sinh(\gamma_x)\cdot Z_0 \\ \sinh(\gamma_x)/Z_0 & \cosh(\gamma_x)/q \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

$$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \frac{1}{2} \times \begin{bmatrix} (q+1/q)\cdot\cosh(\gamma_x) + (Z_0/R_n+R_n/Z_0)\cdot\sinh(\gamma_x) & (q-1/q)\cdot\cosh(\gamma_x) - (Z_0/R_n-R_n/Z_0)\cdot\sinh(\gamma_x) \\ (q-1/q)\cdot\cosh(\gamma_x) + (Z_0/R_n-R_n/Z_0)\cdot\sinh(\gamma_x) & (q+1/q)\cdot\cosh(\gamma_x) - (Z_0/R_n+R_n/Z_0)\cdot\sinh(\gamma_x) \end{bmatrix}$$

two-port matrix parameters, related to waves (asymmetrical q¹1)

$$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \frac{1}{1 - s_{R1}\cdot s_{R2}\cdot s_{Tx}^2} \cdot \begin{bmatrix} s_{R1} - s_{R2}\cdot s_{Tx}^2 & s_{Tx} \Big/ \left(\frac{1}{1-s_R^2} + \frac{(q-1)^2}{4\cdot q}\right) \\ s_{Tx} \Big/ \left(\frac{1}{1-s_R^2} + \frac{(q-1)^2}{4\cdot q}\right) & s_{R2} - s_{R1}\cdot s_{Tx}^2 \end{bmatrix}$$

$$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \left(\frac{1}{1-s_R^2} + \frac{(q-1)^2}{4\cdot q}\right) \cdot \begin{bmatrix} 1/s_{Tx} - s_{R1}\cdot s_{R2}\cdot s_{Tx} & s_{R1}\cdot s_{Tx} - s_{R2}/s_{Tx} \\ s_{R1} / s_{Tx} - s_{R2}\cdot s_{Tx} & s_{Tx} - s_{R1}\cdot s_{R2}/s_{Tx} \end{bmatrix}$$

Table 4*: Expressions for matrix parameters of asymmetric cables*

cascade expressions, using twoport matrix parameters

elementary matrix parameters

$$\mathbf{Z} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} = \frac{1}{z_{22a}+z_{11b}} \cdot \begin{bmatrix} z_{11a}\cdot z_{11b} + \Delta_{za} & +z_{12a}\cdot z_{12b} \\ +z_{21a}\cdot z_{21b} & z_{22a}\cdot z_{22b} + \Delta_{zb} \end{bmatrix} \qquad \Delta_z = z_{11}\cdot z_{22} - z_{12}\cdot z_{21}$$

$$\mathbf{Y} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \frac{1}{y_{22a}+y_{11b}} \cdot \begin{bmatrix} y_{11a}\cdot y_{11b} + \Delta_{ya} & -y_{12a}\cdot y_{12b} \\ -y_{21a}\cdot y_{21b} & y_{22a}\cdot y_{22b} + \Delta_{yb} \end{bmatrix} \qquad \Delta_y = y_{11}\cdot y_{22} - y_{12}\cdot y_{21}$$

$$\mathbf{S} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \frac{1}{1\text{-}s_{22a}\cdot s_{11b}} \cdot \begin{bmatrix} s_{11a}-\Delta_{sa}\cdot s_{11b} & s_{12b} \cdot s_{12a} \\ s_{21a} \cdot s_{21b} & s_{22b}-\Delta_{sb}\cdot s_{22a} \end{bmatrix} \qquad \Delta_s = s_{11}\cdot s_{22} - s_{12}\cdot s_{21}$$

cascade matrix parameters

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} a_{11a} & a_{12a} \\ a_{21a} & a_{22a} \end{bmatrix} \times \begin{bmatrix} a_{11b} & a_{12b} \\ a_{21b} & a_{22b} \end{bmatrix}$$

$$\mathbf{T} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \begin{bmatrix} t_{11a} & t_{12a} \\ t_{21a} & t_{22a} \end{bmatrix} \times \begin{bmatrix} t_{11b} & t_{12b} \\ t_{21b} & t_{22b} \end{bmatrix}$$

Table 5*: Expressions for the matrix parameters of a cascade of two-ports*

All these two-port parameters are functionally the same, but their favorite numerical application may differ. Special care must be attended on avoiding numerical (round-off) errors in the case of lines with zero length, impedance, transmission, reflection or zero frequency. In these cases a few matrix representations may be in favor to the others. Similar warnings hold for cascade calculation in the case of very lossy lines.

S-parameters, normalized to R_N, are relatively simple to obtain when source and load impedance of the measurement equipment are equal to R_N. In this special case, s_{21} equals the voltage gain U_2/U_1.
More generally, s_{ij} represents the ratio between an outgoing wave Ψ_j (reflected or transmitted) and an incoming wave Ψ_i. As a result, the terminology in table 6 is commonly used:

	forward	*reverse*
transmission, @R_N	s_{21}	s_{12}
reflection, @R_N	s_{11}	s_{22}
insertion loss, @R_N	$1 / s_{21}$	$1 / s_{12}$
return loss, @R_N	$1 / s_{11}$	$1 / s_{22}$

Table 6: *Definition of transmission and reflection properties*

2.3. Multi-port matrix parameters

Telephony cables are usually constructed from a multiple of (twisted) metalic pairs. Crosstalk between these pairs is an additional quantity that characterizes cables. This paragraph defines various crosstalk parameters.
The cable structure in figure 1 is essentially a 12-port network (each port is formed by a wire-end and the cable-shielding). Neglecting all common-mode effects yields a (differential mode) 6-port network representation. The well known two-port z-, y- or s-parameter representations can be generalized to represent these multiports.

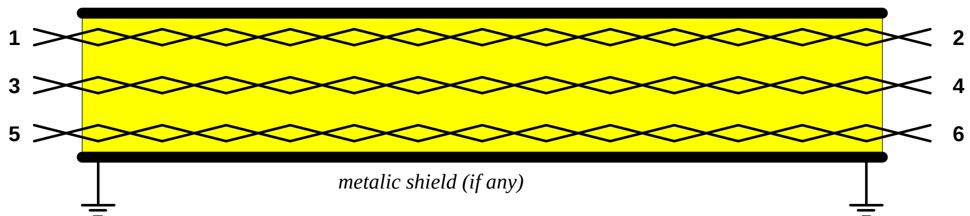


Figure 1*: A cable with three wirepairs is essentially a 12-port network. Neglecting all common mode effects yield a 6-port (differential mode) network representation.*

Near-end (=NEXT) and far-end (=FEXT) crosstalk is measured at equal source and load impedance. This is equivalent with measuring the (differential mode) multiport s-parameters, normalized to R_N.
Equal level FEXT (=EL-FEXT) is a ratio between crosstalk and transfer, and this ratio is indicative for the signal to noise ratio at the receiver side of the cable.
Table 7 defines various crosstalk parameters dealing with wirepair 1-2 and 3-4.

	Forward	*reverse*	*forward*	*reverse*
NEXT - transfer (s_{xn}), @R_N	s_{31}	s_{13}	s_{42}	s_{24}
FEXT - transfer (s_{xf}), @R_N	s_{41}	s_{14}	s_{23}	s_{32}
EL-FEXT - transfer, @R_N	s_{41} / s_{21}	s_{14} / s_{34}	s_{23} / s_{43}	s_{32} / s_{12}
NEXT - loss, @R_N	$1 / s_{31}$	$1 / s_{13}$	$1 / s_{42}$	$1 / s_{24}$
FEXT - loss, @R_N	$1 / s_{41}$	$1 / s_{14}$	$1 / s_{23}$	$1 / s_{32}$
EL-FEXT loss, @R_N	s_{21} / s_{41}	s_{34} / s_{14}	s_{43} / s_{23}	s_{12} / s_{32}

Table 7*: Definition of transmission and reflection properties*

The overall crosstalk level at one port, induced by several uncorrelated sources at other ports, is the power sum of the individual levels that are induced. In the special case that the spectral levels of all these uncorrelated sources are equal, the overall crosstalk level equals the level of one source, multiplied by the associated power-summed crosstalk function. Table 8 defines these functions for port “x”, induced by the ports “y_1”, “y_2” … “y_n”.

power-summed crosstalk-transfer:	$s_{x\P(y1,y2,\ldots)} = \sqrt{\lvert s_{x,y1}\rvert^2 + \lvert s_{x,y2}\rvert^2 + \ldots\ldots}$
power-summed crosstalk-loss:	$1/s_{x\P(y1,y2,\ldots)} = 1/\sqrt{\lvert s_{x,y1}\rvert^2 + \lvert s_{x,y2}\rvert^2 + \ldots\ldots}$

***Table 8**: Definition of power-summed crosstalk functions, that combine the crosstalk induced from several ports. All possible NEXT and FEXT combinations in the sixport in figure [*] are:*
power-summed NEXT-transfer: $s_{1\P(3,5)}, s_{2\P(4,6)}, s_{3\P(1,5)}, s_{4\P(2,6)}, s_{5\P(1,3)}, s_{6\P(2,4)}$
power-summed FEXT-transfer: $s_{1\P(4,6)}, s_{2\P(3,5)}, s_{3\P(2,6)}, s_{4\P(1,5)}, s_{5\P(2,4)}, s_{6\P(1,3)}$

2.4. Cable plant unbalance parameters

The two conductors of a copper pair (twisted or untwisted) may not be electrically balanced with respect to ground. In general, this is not a property related to the cable alone, but to the combination of cable and its environment. This is because ground is an undefined issue in the case of unshielded cables. Unbalance of similar cables will differ between cable plants due to unequal wire installation.

The consequences of cable plant unbalance are twofold:

- A signal that is injected in differential mode to one end of the cable will cause differential mode signals *and* additional common mode signals in that cable. This increases the radiation of signals (egress) due to these common mode components.
- A signal that is injected in common mode to one end of the cable will cause common mode signals *and* additional differential mode signals in that cable. This increases the sensitivity to RFI signals (ingress) that are received in common mode.

As long as the balance of transmission equipment is significantly better than the balance of the cable plant, the egress of the cable is not deteriorated by that equipment. Note that it is not possible to compare the egress or ingress from shielded and unshielded cables by considering unbalance only!

Balance and symmetry are different aspects of cables. The first is a lateral property (about “earth”) and the second is longitudinal property (between “input” and “output” ports).

- For instance, a difference in impedance about earth between the two individual wires at one port is indicative for *lateral unbalance.*
- For instance, the change in reflection due to an interchange of wire pairs between port 1 and 2 is indicative for *reversal asymmetry.*

Differential mode cable measurements are reliable when the balance of the cable is good. A poor (reversal) symmetry does not affect the reliability of differential mode measurements.

Unbalance is normalized to an (arbitrary choosen) real reference impedance R_N. It is recommended [6] to choose this value within 25% of the nominal characteristic impedance Z_0 of the cable. The basic unbalance parameters specify ratio’s between differential mode and common mode signals under various injection conditions.

2.4.1. One-port unbalance about earth

Figure 2 and **3** show a one-port, having two 'floating' nodes and a third 'ground' node. The two floating port nodes are connected to the end of the two wires of a wire pair. The (complex) impedances Z_a, Z_b and Z_c represent the element values of an equivalent circuit diagram of that port. Perfect balance is achieved when $Z_a=Z_b$, or when $(Z_a-Z_b)=\Delta Z_0=0$.
The circuitry around this one-port illustrates how signals can be injected in common mode or in differential mode from a 'floating' source impedance with value R_N. The one-port unbalance parameters, normalized to this R_N, are defined as ratio's between various voltages, as defined in figure 2 and **3**. They are identified as $\{q_L, q_{LL}, q_T, q_{TT}\}$ and named as follows:

Common mode injection (longitudinal conversion)

DCR = Differential mode Conversion Ratio:	q_L
LCR = Longitudinal Conversion Ratio:	q_{LL}
DCL = Differential mode Conversion Loss:	$1/q_L$
LCL = Longitudinal Conversion Loss:	$1/q_{LL}$

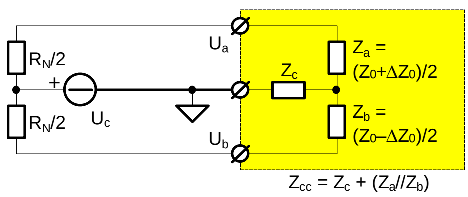
Differential mode injection (transverse conversion)

CCR = Common mode Conversion Ratio:	q_T
TCR = Transverse Conversion Ratio:	q_{TT}
CCL = Common mode Conversion Loss:	$1/q_T$
TCL = Transverse Conversion Loss:	$1/q_{TT}$

The basic quantities $\{q_L, q_T\}$ are directly related common and differential mode voltages. The alternative quantities $\{q_{LL}, q_{TT}\}$ cause a slightly different result, but are recommended [6] when unbalance has to be characterized by a direct measurement.
These differences can often be ignored. Under all conditions the relation $(q_T \equiv q_{TT})$ holds, while in many cases $(q_L \approx q_{LL})$ and $(q_L \approx 2\cdot q_T)$ hold. At 'low' frequencies, Z_{cc} is capacitive in nature, but may becomes real and as low as Z_0 at 'high' frequencies. Under these conditions, q_L is about 2 dB higher than q_{LL}. In general the following relation between q_L and q_{LL} holds:

$$\frac{q_L}{q_{LL}} = 1 + \frac{1}{4\cdot Z_{cc}/R_N + \Delta Z_0^2/Z_0/(Z_0+R_N)} \approx 1 + \frac{R_N}{4\cdot Z_{cc}}$$

Common mode injection (longitudinal conversion)

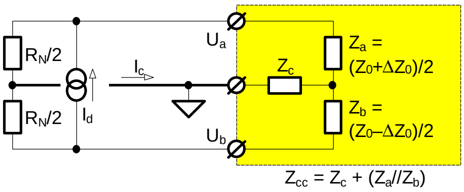


DCR: $$q_L = \frac{U_{diff}}{U_{com}} = \frac{(U_a-U_b)}{\frac{1}{2}\cdot(U_a+U_b)} = \frac{\Delta Z_0}{\frac{1}{2}\cdot(Z_0/R_N+1)\cdot(4\cdot Z_{cc}) + \frac{1}{2}\cdot\Delta Z_0^2/Z_0} \approx \frac{\Delta Z_0}{4\cdot Z_{cc}}$$

LCR: $$q_{LL} = \frac{U_{diff}}{U_{long}} = \frac{(U_a-U_b)}{U_c} = \frac{\Delta Z_0}{\frac{1}{2}\cdot(Z_0/R_N+1)\cdot(4\cdot Z_{cc}+R_N) + \frac{1}{2}\cdot\Delta Z_0^2/Z_0} \approx \frac{\Delta Z_0}{4\cdot Z_{cc}}$$

***Figure 2**: Definition of the conversion of common mode signals into differential mode or longitudinal signals. The parameters q_L and q_{LL} are a slightly different (up to 2 dB when Z_{cc} and R_N are almost equal.*

Differential mode injection (transverse conversion)



CCR: $$q_T = \frac{U_{com}}{U_{diff}} = \frac{\tfrac{1}{2}\cdot(U_a+U_b)}{(U_a-U_b)} = \frac{\Delta Z_0}{(Z_0/R_N)\cdot(8\cdot Z_{cc})+2\cdot Z_0} \approx \frac{\Delta Z_0}{8\cdot Z_{cc}}$$

TCR: $$q_{TT} = \frac{U_{tran}}{U_{diff}} = \frac{I_c\cdot R_N/4}{(U_a-U_b)} = q_T \approx \frac{\Delta Z_0}{8\cdot Z_{cc}}$$

Figure 3*: Definition of the conversion of differential mode signals into common mode or transverse signals. The parameters* q_T *and* q_{TT} *are exactly the same.*

Practical measurement setups on longitudinal and transverse unbalance take usually the advantages of balanced transformers. Figure 4 illustrates the equivalence between the injecting circuitry of figure 2 and 3, and a balanced transformer circuit. See [6] for some recommended measurement setups.

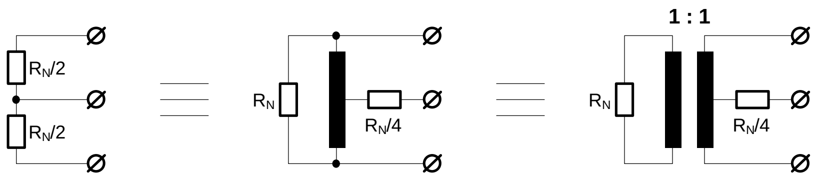


Figure 4*: Equivalence between a center tapped resistor network and a balanced transformer network.*

2.4.2. Multi-port unbalance about earth

The unbalance at one port of a multi-port, normalized to R_N, is defined while all other ports are terminated with that reference impedance R_N. Additional unbalance parameters can be defined by including the transfer between two ports. They specify for instance the converted common mode signal at one port while a differential mode signal is injected at another port. The definition of these additional parameters is somewhat similar to the one-port unbalance parameters. A description can be found in [6]. These parameters are identified as:

Common mode injection (longitudinal conversion)
DCTR = Differential mode Conversion Transfer Ratio
LCTR = Longitudinal Conversion Transfer Ratio
DCTL = Differential mode Conversion Transfer Loss
LCTL = Longitudinal Conversion Transfer Loss

Differential mode injection (transverse conversion)
CCTR = Common mode Conversion Transfer Ratio
TCTR = Transverse Conversion Transfer Ratio
CCTL = Common mode Conversion Transfer Loss
TCTL = Transverse Conversion Transfer Loss

3. Formal description of cable models

3.1. Two-port modelling

3.1.1. The BT#x two-port models, focussed on $\{Z_s, Y_p\}$

The empirical model BT#1 of British Telecom [9,10] is focussed on modelling $\{Z_s, Y_p\}$. The model is able to predict the cable characteristics from DC to tens of MHz,.and is shown in table 10.

[BT#0]

$$Z_s(f) = \sqrt[4]{R_{oc}^{\,4} + a_c \cdot f^{\,2}} + j \cdot 2\pi f \cdot \left(\frac{L_0 + L_\infty \cdot (f / f_m)^{Nb}}{1 + (f / f_m)^{Nb}} \right) \quad [\Omega/\text{km}]$$

$$Y_p(f) = (g_0 \cdot f^{Nge}) + j \cdot 2\pi f \cdot (C_\infty + C_0 / f^{Nce}) \quad [\text{S/km}]$$

Table 9*: The formal “BT#0” model for cable parameters, using 11 line constants for a range from DC to a maximum frequency.*

[BT#1]

$$Z_s(f) = \left(\frac{1}{\sqrt[4]{R_{oc}^{\,4} + a_c \cdot f^2}} + \frac{1}{\sqrt[4]{R_{os}^{\,4} + a_s \cdot f^2}} \right)^{-1} + j \cdot 2\pi f \cdot \left(\frac{L_0 + L_\infty \cdot (f / f_m)^{Nb}}{1 + (f / f_m)^{Nb}} \right) \quad [\Omega/\text{km}]$$

$$Y_p(f) = (g_0 \cdot f^{Nge}) + j \cdot 2\pi f \cdot (C_\infty + C_0 / f^{Nce}) \quad [\text{S/km}]$$

Table 10*: The formal “BT#1” model for cable parameters, using 13 line constants for a range from DC to a maximum frequency. Note that when* R_{os} *and* a_s *goes to infinity, the model BT#1 reduces to the BT#0 model*

3.1.2. The KPN#x two-port models, focussed on $\{Z_s, Y_p\}$

The empirical models KPN#0 and KPN#1 of the Royal PTT Netherland [13], is focussed on modelling $\{Z_s, Y_p\}$. These models are significantly different from the BT#1 and the DTAG#1 model because they describe the skin effect in a way that is closer related to the underlying physics. As a result, no more than four line constants control the dominant behavior. Seven empirical line constants have been added for fine tuning purposes, but two of them seem to be superfluous in practice. The KPN models are shown in table 11 and 12 and are able to predict the cable characteristics from DC to tens of MHz.

[KPN#0]

$$Z_{s0}(\omega) = j\cdot\omega\cdot Z_{0\infty} / c + R_{ss00}\cdot(1/4 + \chi\cdot\coth(4/3\chi)) \quad [\Omega/m]$$

$$Y_{p0}(\omega) = j\cdot\omega/Z_{0\infty} / c + (\tan(\phi)/Z_{0\infty})/c\cdot\omega \quad [S/m]$$

$$\chi = \chi(\omega) = (1+j)\cdot\sqrt{\frac{\omega}{2\pi}\cdot\frac{\mu_0}{R_{ss00}}}$$

***Table 11**: Simplified "KPN#0" model, based on only 4 line constants, to describe the dominant behavior of cables. In these expressions $\mu_0=4\cdot\pi\cdot10^{-7}$ [H/m] represents the permeability of vacuum, and c the propagation speed (lower than the speed of light $c_0=3\cdot10^8$ [m/s]). The asymptotic series inductance and shunt capacitance are equal to $L_{s\infty} = Z_{0\infty}/c$ en $C_{p\infty}=1/(c\cdot Z_{0\infty})$.*

[KPN#1]

$$Z_{s0}(\omega) = j\cdot\omega\cdot Z_{0\infty}\cdot 1/c + R_{ss00}\cdot(1 + K_l\cdot K_f\cdot(\chi\cdot\coth(4/3\chi) - 3/4)) \quad [\Omega/m]$$

$$Y_{p0}(\omega) = j\cdot\omega/Z_{0\infty}\cdot 1/c\cdot(1 + (K_c-1) / (1+(\omega/\omega_{c0})^N)) + \tan(\phi)/(Z_{0\infty}\cdot c)\cdot\omega^M \quad [S/m]$$

$$\chi = \chi(\omega) = (1+j)\cdot\sqrt{\frac{\omega}{2\pi}\cdot\frac{\mu_0}{R_{ss00}}\cdot\frac{1}{K_n\cdot K_f}}, \quad \omega_{c0}=2\pi\cdot f_{c0}$$

***Table 12**: The formal "KPN#1" model that is more realistic than the KPN#0 model. It is based on eleven line constant for a range from DC to a maximum frequency. In many cases $K_n=1$ and M=1 will suffice.*

3.1.3. The MAR#x two-port models, focussed on $\{Z_s,Y_p\}$

The empirical models MAR#1 and MAR#2 [16] have some similarity with the KPN#0 model, but respects the Hilbert condition between the real and imaginary parts of Z_s and of Y_p. This condition is essential to facilitate cable models having a *real* impulse response. Some of the models in this overview predict impulse responses that have also an imaginairy part, which is meaningless and a handicap for time domain simulations. The MAR#x models are defined in [16], and will be added to this overview in a succeeding version of this reference document.

3.1.4. The DTAG#1 two-port model, focussed on $\{\gamma,Z_0\}$

The empirical model DTAG#1 of Deutsche Telekom AG [11] is focussed on modelling $\{\gamma,Z_0\}$ rather than modelling $\{Z_s,Y_p\}$. This model is unable to span a whole frequency range from DC to 30MHz because that will result in a noticeable difference between the model and the measurement. For example for a 0.35 mm cable of length 100 m, the difference is 0.16 dB at 400 kHz. If the formula is used for a simulation of a 3 km long cable, there would be an error of 4.8 dB [11].
Therefore, a piecewise approximation of the attenuation coefficient should be used to reduce the difference between model and measurement to below 0.006 dB (100m), if the frequency range between 0 and 30 MHz is divided into 3 ranges. This approach was restricted to $\alpha(f)$, which has excluded the validation for Z_0 below 75kHz. [11]. The model is shown in table 13.

[DTAG#1]	
$\gamma(f) = \left(K_{a1} + K_{a2} \cdot (f/10^6)^{K_{a3}}\right) \cdot \frac{\ln(10)}{20} + j \cdot \left(K_{b1} \cdot (f/10^6) + K_{b2} \cdot \sqrt{f/10^6}\right)$	[1/km]
$Z_0(f) = \left(K_{z1} + K_{z2} / (f/10^6)^{K_{z3}}\right) \cdot exp\{ \left(-j \cdot K_{x1}\right) / \left((K_{x2} + f/10^6)^{K_{x3}}\right) \}$	[Ω]
$Z_s(f) = \gamma \cdot Z_0$	[Ω/km]
$Y_p(f) = clip\{re(\gamma/Z_0)\} + j \cdot im(\gamma/Z_0)$	[S/km]

***Table 13**: The formal "DTAG#1" model for cable parameters, using 11 line constants per frequency range. The clip-function is a function with the property that clip(+x)=x and clip(–x)=0 for all positive values of x. It is essential to calculate the matrix parameters from* $\{Z_s, Y_p\}$, *and not from* $\{\gamma, Z_0\}$, *because the quotient* (γ/Z_0) *tends to unrealistic values with negative real parts at 'low' frequencies.*

3.1.5. The SWC#1 two-port model, focussed on {g,Z_0}

The empirical model SWC#1 of Swisscom [17] is focussed on modelling $\{\gamma, Z_0\}$ rather than modelling $\{Z_s, Y_p\}$. The model can be valid over a wide frequency range, but tends to become unrealistic for low frequencies (eg below 10 kHz). This is typical for models that are focussed on $\{\gamma, Z_0\}$. This restriction might be irrelevant for frequency domain simulations but could be a handicap for time domain simulations.

[SWC#1]	
$Z_0(f) = Z_{00} \cdot (1 + f_1/f)^{N_{e1}} \cdot exp\{j \cdot (-\pi/4 + c_1 \cdot atan(f/f_2))\}$	[Ω/m]
$\gamma(f) = c_2 \cdot \frac{ln(10)}{20} \cdot \left(\frac{1 + f/f_4}{1 + f_3/f}\right)^{N_{e2}} + \frac{j\pi}{180} \cdot c_3 \cdot \left(\frac{f}{f_5}\right)^{N_{e3}} \cdot \left(1 + \frac{f}{f_5}\right)^{N_{e4}}$	[S/m]

***Table 14**: The formal "SWC#1" model for cable parameters, using 13 line constants.*

3.2. Power-summed crosstalk modelling

The purpose of crosstalk modeling is to predict the spectral density of the crosstalk signal in a wire-pair, induced by disturbing modems in adjacent wire pairs. There are some restrictions to account for. Crosstalk is very random in nature because it originates from imperfections in cables. The crosstalk transfer function differs from wire-pair combination to wire-pair combination. These differences can be significantly: up to tens of dB between the worst and best wire-pair combination. Crosstalk can even *reduce by extending* the cable length, due to extinguished interference. This makes that several restrictions are to be considered when applying crosstalk models to simulations.

Two classes of crosstalk simulations are to be considered, simulating crosstalk induced by a small or by a large number of disturbers.

- Simulating a small number of disturbers is often associated with large uncertainties, when they are based on one averaged crosstalk model. This means one model for a whole multi wire-pair cable. Due to the random nature of crosstalk between *individual* wire-pair combinations, the use of an averaged crosstalk model is often inadequate. The associated uncertainty is maximal when information on the geometric position in the cable of the modeled wire-pairs is not included in the model. Using different crosstalk models will overcome this large uncertainty but the huge number of models that are involved with this approach makes it not a preferred strategy. In general, avoid simulations on a small number of disturbers when it is based on averaged crosstalk models.
- Simulating a large number of disturbers with averaged crosstalk models yields much better and reliable results. The more disturbers that are involved the lower this uncertainty can be. Assume a cable, with 900 wire-pairs in the same binder group, and determine the power induced by 50 identical disturbers from arbitrary adjacent wire pairs. The huge number of wire-pair combinations will all result in different power levels, but the distance in dB between worst-case and best-case crosstalk level is significantly reduced, compared to the single disturber case.

The crosstalk models that are summarized in this document are all models, averaged over the full cable (or binder group). They model the power-summed crosstalk functions, as defined in table 8. Their validation is restricted to a large number of disturbers and they deteriorate in predicting performance when this number is significantly lowered.

3.2.1. Normalized power-sum scaling functions

A power-sum scaling function $\Phi(N)$ scales the power sum crosstalk from N_1 disturbers to N_2 disturbers, provided that N_1 as well as N_2 are significantly larger than 1. It is widely accepted that the worst crosstalk comes from the closest (few) wire pairs, which means that the summed power cannot increase proportionally with the number of disturbers. Once, when all wire-pairs adjacent to the reference one are occupied, the additional disturbers contribute at a lower level to the overall crosstalk power. Although not valid for N=1, this document is restricted to normalized scaling functions that satisfy $\Phi(1)=1$. A commonly used ANSI scaling function [4,5] is illustrated in table 15. Alternative scaling functions [25] are subjects for further study.

$$\Phi(N) = (N)^{K_m} \qquad (N \gg 1)$$

Table 15*: The formal power-sum scaling function, with N the number of disturbers, and K_m a constant in the order of 0.3.*

Most power-sum scaling functions have one fundamental discrepancy in common. They are inevitable not consequent in their prediction when scaling the number of disturbers.

- On one hand, the crosstalk power does not increase linearly with the number of disturbers. The commonly used ANSI [4,5] scaling function (K_m=0.3) predicts that an increase from 50 disturbers to 500 identical disturbers results in about 6dB increase of induced crosstalk power.

- On the other hand, crosstalk models are used to predict the crosstalk power for a mix of different disturbers. When the crosstalk models predicts that the noise level of 50 disturbers is not 3dB higher than that from 25 disturbers, the simulation suffers from a fundamental discrepancy. For the commonly used ANSI crosstalk model [4,5], this discrepancy equals about 1.2 dB at 2×25 disturbers, about 1.9 dB at 3×16 disturbers and about 2.4 dB at 4×12 disturbers, compared to the 1×49 case.

Be aware of this when using power-sum scaling functions.

3.2.2. Power-summed crosstalk models X#0

The crosstalk models "X#0" are pure empirical models [4,5], and are kept as simple as possible. They are valid only for long cables. The power-summed crosstalk of N disturbers at frequency ω and length x is expressed as:

NEXT:	$|s_{xn¶}(N,\omega)| \approx \Phi(N) \cdot K_{xn} \cdot (\omega/\omega_0)^{K_w}$	(N >>1)
FEXT:	$|s_{xf¶}(N,\omega,x)| \approx \Phi(N) \cdot K_{xf} \cdot (\omega/\omega_0) \cdot (x/x_0)^{K_L} \cdot s_{T0}$	

***Table 16**: The formal crosstalk models "X#0", valid only when N>>1*
s_{xn}, s_{xf} are the spectral amplitude densities (root of spectral power density) of the crosstalk
s_{T0} is the average transfer (s_{21}) of the wire pairs, at length x
Φ(N) is a normalized power-sum scaling function, with N the number of disturbers
K_{xn} is a NEXT coupling constant, at frequency ω_0
K_{xf} is a FEXT coupling constant, at length x_0 and frequency ω_0
K_w is an empirical exponent, usually in the order of 0.75
K_L is an empirical exponent, usually in the order of 0.5
x_0 is an arbitrary chosen length, usually the unit length (1 m)
ω_0 is an arbitrary chosen frequency, usually the unit frequency ($2\pi \cdot 1$ Hz)

3.2.3. Power-summed crosstalk models X#1

The crosstalk models "X#1" have more theoretical basis [7,8], and include a length correction for the power-summed NEXT of short cables. The power-summed crosstalk of N disturbers at frequency ω and length x is expressed as:

NEXT:	$|s_{xn¶}(N,\omega,x)| \approx \Phi(N) \times \dfrac{\omega \cdot R_N \cdot C_{xxn}}{2\cdot\sqrt{\alpha}} \times \sqrt{1-exp(-4\cdot\alpha\cdot x)}$	(N >>1)
FEXT:	$|s_{xf¶}(N,\omega,x)| \approx \Phi(N) \times (½\cdot\omega\cdot R_N\cdot C_{xf}) \cdot (x/x_0)^{K_L} \times s_{T0}$	

***Table 17**: The formal crosstalk models "X#1", valid only when N>>1*
s_{xn}, s_{xf} are the spectral amplitude densities (root of spectral power density) of the crosstalk
s_{T0} is the average transfer (s_{21}) of the wire pairs, at length x
Φ(N) is a normalized power-sum scaling function, with N the number of disturbers
R_N the chosen reference impedance (e.g. 135 Ω for VDSL)
C_{xxn} is a NEXT scaling constant
C_{xf} is a FEXT equivalent capacitance, at length x_0
K_L is an empirical exponent, usually in the order of 0.5
α = re(γ) = is the average transmission coefficient per unit length of the wire pairs
x_0 is an arbitrary chosen length, usually the unit length (1 m)

Each cable segment contributes to the overall crosstalk; this contribution can be equal for each segment, at random or everything in-between. In the case of a pure systematic coupling (K_L=1), the crosstalk adds on a voltage base, and its level in dB scales with $20\cdot{}^{10}\log(x)$. In the case of a pure random coupling (K_L=0.5), the crosstalk adds on a power base, and its level in dB scales with $10\cdot{}^{10}\log(x)$.

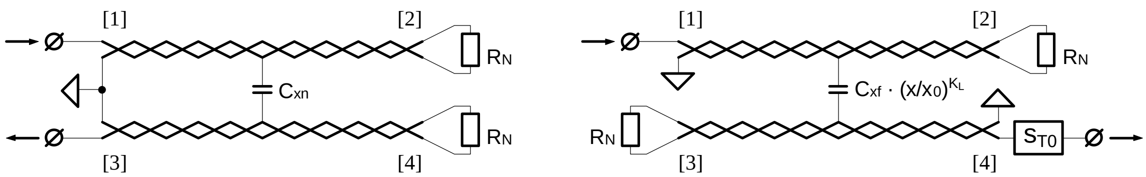
3.2.4. Power-summed crosstalk models X#2

These models are a modification of the previous formal models. The NEXT is simplified by substituting α with a function proportionally to $\sqrt{\omega}$:

NEXT:	$\lvert s_{xn¶}(N,\omega,x)\rvert \approx \Phi(N) \times (½\cdot R_N\cdot C_{xn}) \cdot \omega_0^{(1-Kw)} \cdot \omega^{Kw} \times \sqrt{1-exp(-4\cdot\alpha\cdot x)}$	(N >>1)
FEXT:	$\lvert s_{xf¶}(N,\omega,x)\rvert \approx \Phi(N) \times (½\cdot R_N\cdot C_{xf}) \cdot (x/x_0)^{K_L} \cdot \omega \times s_{T0}$	

Table 18*: The formal crosstalk models "X#2", valid only when N>>1*
s_{xn}, s_{xf} are the spectral amplitude densities (root of spectral power density) of the crosstalk
s_{T0} is the average transfer (s_{21}) of the wire pairs, at length x
F*(N) is a normalized power-sum scaling function, with N the number of disturbers*
*R_N the chosen reference impedance (e.g. 135**W** for VDSL)*
*C_{xn} is a NEXT equivalent capacitance, at frequency **w**$_0$*
C_{xf} is a FEXT equivalent capacitance, at length x_0
***w**$_0$ is a chosen center frequency, usually in the order of 2**p**·1 MHz*
K_L is an empirical exponent, usually in the order of 0.5
K_w is an empirical exponent, usually in the order of 0.75
***a** = re(**g**) is the average transmission coefficient per unit length of the wire pairs*
x_0 is an arbitrary chosen length, usually the unit length (1 m)

The rational behind a NEXT formulation with an addition ω_0 parameter is to simplify the extraction of equivalent crosstalk networks. Figure 5 illustrates this equivalence with a pure capacitive network at specified frequency ω_0 (in the case of NEXT) or at specified length x_0 (in the case of FEXT).



[A] NEXT equivalence, at specified frequency *[B]FEXT equivalence, at specified length*

Figure 5*: Equivalent networks for NEXT and FEXT. The Next equivalence is valid only at the specified frequency, since the frequency dependency of NEXT differs from a pure capacitor.*

3.3. Unbalance modelling

Table 19 summarizes three different empirical models on the Longitudinal Conversion Loss, as defined in figure 2. Although a linear specification of this ratio is shown, a logaritmic (dB) specification is commonly used. In the first two models, the constant K_{u1} equals the LCL in dB at the (arbitrary chosen) center frequency f_0.
The models "LCL#1" and "LCL#2" can have similar behaviour within the range of 1 MHz to 30 MHz, but are different at lower frequencies. Model LCL#3 is a modification of LCL#3 and takes account for the line length x.

LCL#1: $\|q_{LL}(\omega)\| = \left\{ 10^{(K_{u1}/20 \; - \; K_{u2} \cdot {}^{10}\log(\omega/\omega_0))} \right\}$
LCL#2: $\|q_{LL}(\omega)\| = \left\{ 10^{(K_{u1}/20)} \cdot (\omega/\omega_0)^{-K_{un}} \right\}$
LCL#3: $\|q_{LL}(\omega,x)\| = 10^{\Psi(\omega,x)/20}$; $\Psi(\omega,x) = 10^{(K_{ua} \cdot x^{K_{ub}})} \times (\omega/\omega_0)^{(K_{uc} \cdot x^{K_{ud}})}$

$\omega_0 = 2\pi \cdot f_0$

Table 19*: Two formal LCL models on Longitudinal Conversion Loss. The are based on two or three line constants, and an arbitrary chosen center frequency* f_0.

4. Measurement examples on an arbitrary test cable

Some cable parameters tend to become random in nature when the length of the cable is hundreds of meters or more. This means that simulation models are usually unable to provide an exact description of the cable characteristics.
Good models for simulation purposes are characterized by an excellent description of transmission aspects in operational situations, at the cost of a moderate description of other aspects. A good match to transmission parameter s_{21} (especially accurate at high frequencies) and a moderate match to characteristic impedance Z_0 (especially accurate at low frequencies) is usually much better than a model that is optimized to fit the primary cable parameters with the lowest possible error [13].
The aim of this paragraph is to illustrate the difference between measured and modelled cable parameters, by an example of an arbitrary twisted pair cable. This example has been taken from the KPN results of a round robin test on cable measurements [14], that various operators and manufacturers have used to validate and improve their measurement methods. Joining the experiment is open for anyone that is willing to share the measured results in an electronic way with the other participants.

4.1. The KPN test cable #1

By the end of 1996, KPN has constructed a portable box, containing a long twisted pair cable [14]. This test cable construction enables reproducable measurements on (differential mode) transfer, reflection and crosstalk characteristics. It is a metalic box of 34×34×32 cm, it weights 15.5 kg, and is filled with nearly 400 m indoor cabling. In combination with the 45×45×45 cm wooden transport container, it weights 25 kg.
The cable itself is unshielded and has two 0.5 mm pairs in a twisted quad. The overall construction is very stable and robust, because all free space in the box has been filled-up with foam. This enables reproducable measurements.
KPN has measured the four-port (differential mode) s-parameters of this test cable, normalized to 135 ohm, and shared them with other participants of the round robin test in an electronic way. This reference impedance has been adopted in the ETSI technical report on VDSL as design impedance, and is also used for HDSL. All other cable parameters have been extracted from these s-parameters.

4.2. Measurements on test cable #1

Figure 6 shows the magnitude of the measured four-port s-parameters on the 400 meter cable in the testbox. The numbering of the four ports follows the conventions as illustrated in figure 1.
These four-port (differential mode) s-parameters, normalized to R_N=135Ω, were combined from four independent two-port s-parameter measurements, while all unused ports were terminated by resistors having R_N as value.
All linear systematic errors of the network analyzer and balanced transformers have been eliminated from the measurements, by using a dedicated calibration method.

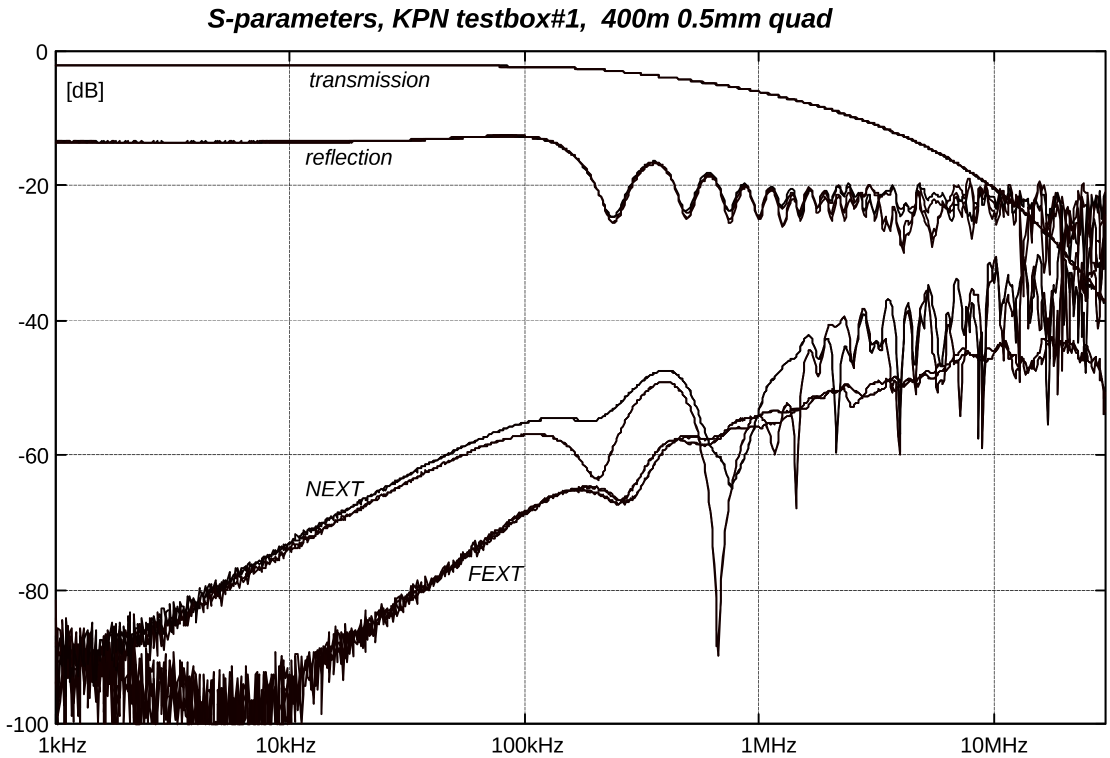


Figure 6 *Measured four-port s-parameters on the KPN Test cable #1, normalized to R_N= 135**W**.*

Description of the measurement setup

The measurement setup is schematically shown in figure 7. NWA refers to a two-port Network Analyzer (HP8751a) and a 50Ω multi-port testset (HP4380, used in two-port mode). Each port has been extended with a 50Ω coaxial cable (40cm), a balanced transformer (North Hills 0415LB) that transforms 50Ω into 150Ω, and a shielded twisted pair connection cable (1.70m). This shield is connected with the transformer cabinet and (via the coaxial cable) with the analyzer. The center tap of the transformer is not grounded. Connecting the shield of the twisted pair connection cable to the cabinet of the testbox did not result in noticable differences.

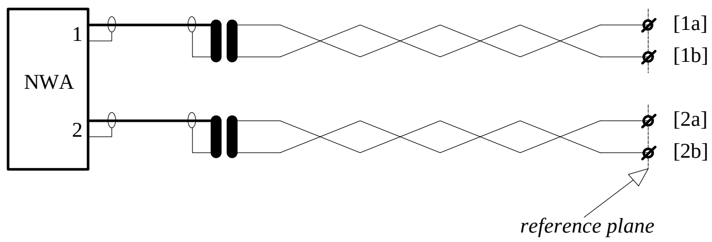


Figure 7 *Measurement setup. Transformers and connection cables are part of the setup, and their influence have been eliminated from the cable measurements by calibrating the setup at the reference planes.*

The reference plane is the 'interface' beween measurement setup and cable under test. Seen from the measurement side, it was positioned at the end of the shielded twisted pair cables. Seen from the testbox side, it was positioned directly at the input of the cable; this is where the wires are soldered on the (green) connector blocks of the testbox.

Description of the calibration method

All linear systematic errors of analyzer and transformers (up to the reference plane) were eliminated from the measurements, by using a dedicated calibration method. As a result, the connection cables and

transformers are ***no*** part of the cable under test. KPN estimates [14] that the calibration has positioned the reference plane at a location that is accurately known within ±2mm.
Calibration was carried out by means of a symmetric (floating) callibration[6] set, which is nothing more than (1) a small sized resistor R_N as *load*, (2) a wire as *short*, (3) a 'nothing' as *open* and (4) a connection as *thru*. This approach results in accurate s-parameters, normalized to R_N, without any change of the build-in calibration software of the network analyzer.
KPN has chosen R_N=150 Ω, so a mathematical transformation was performed afterward from 150 Ω s-parameters into 135 Ω s-parameters. If a value of R_N=135 Ω was chosen, then the 135 Ω s-parameters could be obtained directly from the network analyzer.
Since this approach yields very accurate results, it was noticed that saturation (in the transformer) could be the remaining limitation [14]. For that reason the source power of the network analyzer was reduced a few dB during two-port measurements between port 1-2 and between port 3-4.

4.3. Two-port modelling on test cable #1

Two-port modelling of the individual wire pairs, while ignoring the crosstalk between them, has been performed on the basis of the KPN#1 model (see table 12). The line constants are summarized in table 20. Line “KPN_d1x” refers to the two-port between port 1 and 2 (see labels on the testbox), and line “KPN_d1y” refers to port 3 and 4. These models have been extracted to fit the s-parameters.

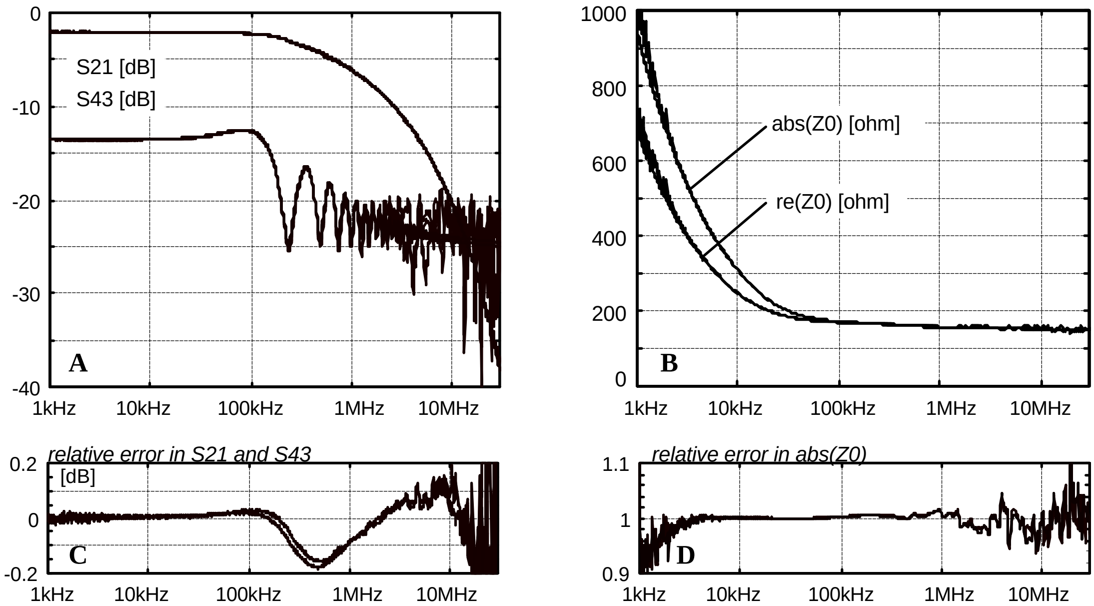


Figure 8 *Measured transmission and characteristic impedance of the two wire pairs of 400m. The measured curves in plots A and B are overlayed with the modeled curves. The difference between measurents and models are shown in plot C and D.*

[6] Connect a resistor R_N between terminal “1a” and “1b”, and a second resistor R_N between terminal “2a” and “2b”, when a “full 2-port” calibration procedure requires *loads*. Connect terminal “1a” with “1b”, and “2a” with “2b” when the procedure requires a *short*. Leave all terminals unconnected when an *open* is required. Connect terminal “1a” with “2a”, and “1b” with “2b” using the shortest possible wires when *thru’s* are required. The ultimate precision will be achieved when the callibration resistors are mounted in indentical connector blocks that are used for connecting the cable under test with the measurement setup. Verify that the cal-kit constants (e.g. offset) in the analyzer match with the layout of the *short*, *load*, *open*, and *thru*. This method can be made reliable up to hundreds of MHz, because it is mainly limited by the construction layout rather than the frequency response of the resistor itself.

	$Z_{0\infty}$	c/c_0	R_{ss00}	$2\pi\cdot\tan(\phi)$	K_f	K_l	K_n	K_c	N	f_{c0}	M
KPN_d1x	149.673	0.70664	0.178969	0.0312794	0.82	1.1	1	1.02764	1	100000	1
KPN_d1y	150.593	0.70265	0.180989	0.0338506	0.78	1.1	1	1.02999	1	167076	1

Table 20: *Line constants for the wire pairs of the test cable #1, using the KPN#1 model (see table 12). KPN_d1x refers to the two-port between port 1 and 2; KPN_d1y refers to port 3 and 4.*

Figure 8A compares this model with the transmission (s_{21}, s_{43}) and figure 8B the extracted characteristic impedances of the two wirepairs. The relative errors between modelled and measured data are shown in figure 8C and 8D.

Figure 9 shows the extracted primairy parameters $\{R_s,L_s,G_p,C_p\}$ of the 400m cable, based on the measurements as well as the model. Twisted pair cables are a little bit inhomogeneous in nature, which causes small differences between 'identical' sections. Especially when cables are long, this effect gives parameters such as R_s and G_p a very random appearance as the frequency increases. This is because very small differences in s-parameters of long cables are 'exploded' to large differences in parameters such as R_s and G_p.
As a result, the individual value of one primary parameter is not particularly meaningful when it is not observed in connection with the other primairy parameters [13]. Therefore, the modelled parameters are not obtained from *individual* fits to these primary parameters, but from a *combined* fit to the two-port parameters.

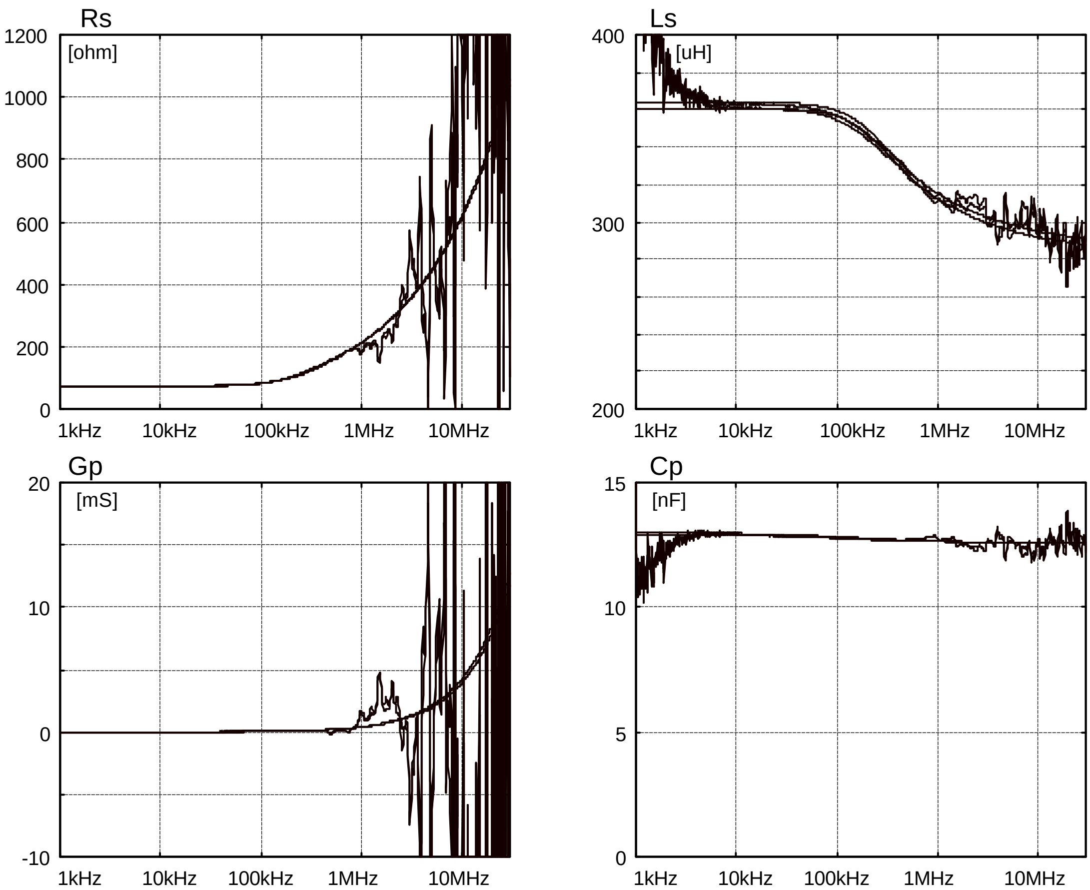


Figure 9 *Extracted primairy cable parameters of the 400m test cable, overlayed by curves generated from the cable model of table 31. The plots show that R_s and G_p become very random in nature as the frequency increases. As a result, their actual value, extracted from real measurements, is not particularly meaningful.*

4.4. Crosstalk modelling on test cable #1

Crosstalk can be approximated by straight lines on a log-log plot. Figure 10 illustrates this for NEXT (s_{xn}), and for Equal Level FEXT which is the average FEXT (s_{xf}) scaled by the average transmission (s_T). The associated line-equations can be expressed in various ways, for instance as summarized in table 21. The advantage of this representation is that the constants C_{xn} and C_{xf} can be interpreted as a 'differential crosstalk capacitance' between the two wire pairs.

NEXT:	$\lvert s_{xn} \rvert \approx (½\cdot R_N\cdot C_{xn}) \cdot \omega_0^{0.25} \cdot \omega^{0.75}$	C_{xn} = 11.7pF C_{xf} = –0.5pF/√m
EL-FEXT:	$\lvert s_{xf} / s_T \rvert \approx (½\cdot R_N\cdot C_{xf}) \cdot \sqrt{x/x_0} \cdot \omega$	R_N = 135Ω, x_0=1m, $\omega_0/2\pi$=1MHz

Table 21 *Constant and equations for a simple modeling of the crosstalk shown in figure 10. Note that it has not been verified if scaling of FEXT is proportional with Öx or not.*

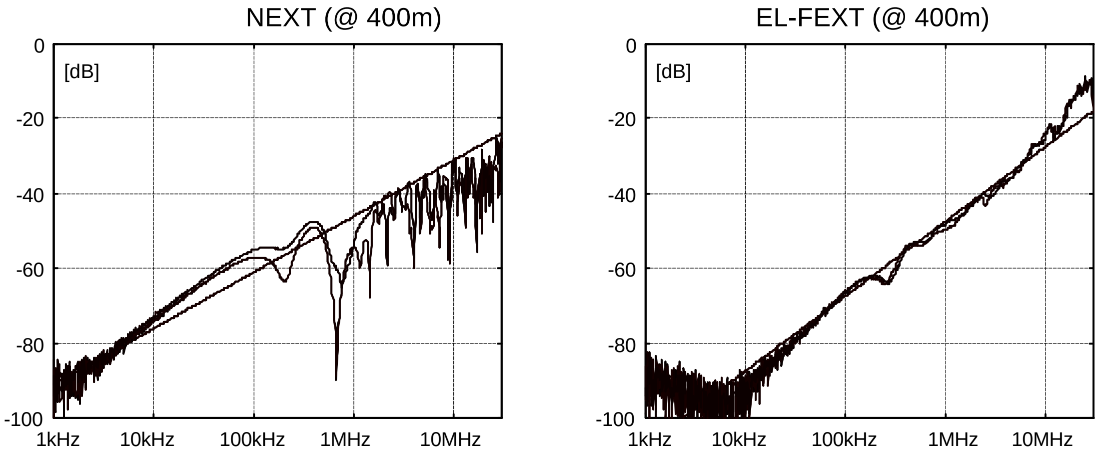


Figure 10 *Plots of near end crosstalk, and equal-level far end crosstalk. The curves are overlayed with straight lines, following the equations of table 21.*

PART 2 - *operator specific data*

5. Two-port line constants for various access cables

This paragraph details for various countries the typical cable parameters variation with frequency for a number of cable types which are representative of their existing metallic access networks.
The wire-pairs are normally twisted, using copper conductors. Burried cables are normally screened (per bundle) while aerial and indoor cable are normally unscreened.

5.1. United Kingdom (*British Telecom*)

Description of cables and network
DW is a acronym for Drop Wire and the DWUG cable type may be taken as representative of 0.5 mm PE insulated underground distribution cabling [9]. The cables BT_dw8, BT_dw10 and BT_dw12 are the most common dropwire types used in the BT access network.
A description of the modelled cables is summarized in table 22.

Description

BT_dw1	Single pair 0.91 mm cadmium copper conductors	PVC insulated No steel strength member
BT_dw3	Single pair 0.72mm (0.028 inch) copper covered steel conductor	PVC insulated No steel strength member
BT_dw5	3-wire (pair and earth) dropwire 0.72mm copper covered steel	PVC insulated No steel strength member
BT_dw6	Single pair 0.81 mm copper covered steel conductor	PVC insulated No steel strength member
BT_dw8	Single pair Flat twin (i.e. untwisted) 1.14 mm cadmium copper conductors	PVC insulated No steel strength member
BT_dw10	2 pair 0.5 mm copper conductors	PVC insulated conductors PVC insulated steel strength member Polyethylene sheath
BT_dw12	Single pair 0.9 mm copper conductors	Polyethylene insulated conductors PVC covered steel strength member Polyethylene sheath
BT_dwug	Multiple pair 0.5 mm solid copper conductors	Polyethylene insulated Predominantly used for underground distribution

Table 22*: Description of the construction of British cables*

Description of measurements
The principle of primary parameters measurements was based on the experimental determination of the complex input impedance (or reflection) of the cable at one end when the other end is either in short circuit or in open circuit..
The measurements were split in two frequency bands [9].

- for frequencies below 1 MHz, the cables under test had a length of 10 m.
- for frequencies ranging from 2 MHz to 20 MHz, the cables under test had a length of 1 m

The parameters $\{\gamma,Z_0\}$ and $\{Z_s,Y_p\}$ are all extracted from these measurements.
Extrapolation to long lengths is checked by predicting the insertion loss of a long cable length from the extracted parameters and comparing it with an actual insertion loss measurement of the cable.
All measurements were carried out to 100 MHz and 20 MHz is the range over which the measurements have been found to be reasonably accurate. Accuracies of ≈ 1% of the insertion loss have been found typical to 10 MHz, 2-3% to 20 MHz, although spreads among pairs and cable instances can be much larger (10-15%).

Description of the models

The line constants for British cables using the BT#1 model, specified in table 10, are summarized in table 23. They are valid up to 20MHz. The typical values may be calculated at any frequency by using the empirical model. The parameter values are given in table 24.

Wire type	R_{oc} N_b	a_c g_0	R_{os} N_{ge}	a_s C_o	L_o C_∞	L_∞ N_{ce}	f_m
BT_dw1	65.32 1.30698	2.7152831e-3 855e-9	0.0 0.746	0.0 46.5668e-9	0.884242e-3 28.0166e-9	800.587e-6 0.117439	263371
BT_dw3	335.180 1.12676	5.35389e-3 137.182e-9	1281.3 0.807645	30286.34 34.431082e-9	1.14166e-3 24.446503e-9	708.221e-6 0.06589	15211
BT_dw5	335.321 1.52968	10.996373e-3 32.574128e-9	1116.45012 0.919	13175.463 31.60789e-9	1.13771e-3 29.297887e-9	792.766e-6 0.1115489	20842.6
BT_dw6	270.70256 1.35790	2.48956e-3 360e-9	774.23224 0.777	3349.76 39.4114e-9	1.10646e-3 27.8941e-9	760.267e-6 0.106593	15668
BT_dw8	41.16 1.1952665	1.2179771e-3 53.0e-9	0.0 0.88	0.0 31.778569e-9	1e-3 22.681213e-9	910.505e-6 0.11086674	174877.
BT_dw10	180.93 0.75577086	49.7223e-3 89.041038e-9	0.0 0.85606301	0.0 63.824345e-9	0.7288683e-3 50.928328e-9	543.4352e-6 0.11584622	718888.
BT_dw12	55.460555 0.93970931	4.9924627e-3 20e-9	0.0 0.88	0.0 5.8022458e-9	0.62104396e-3 51.128076e-9	461.954e-6 0.10064577	193049.
BT_dwug	179 1.2	35.89e-3 0.5e-9	0.0 1.033	0.0 1e-9	0.695e-3 55e-9	585e-6 0.1	1e6

Table 23*: Line constants for British cables, using the BT#1 model (see table 10)*

Comparisons of predicted versus actual insertion loss are carried out to 100 MHz as a validation check. The parameterisation extrapolates reasonably well and does not suddenly stop working at 20 MHz. On some cable types with twisted pairs and PE insulation accuracy is good to 100 MHz.

Typically measurements are made from various pairs and cables of the same generic type. Fits are made to the Z_s and Y_p deduced from each measurement. Fit parameters are then compromised by taking median values of the various measurements. For some of the rarer cable types where only a single sample is available (e.g. BT_dw5) no mediation has been possible except among different short lengths from the same cable sample.

	Frequency (Hz)	Resistance (Ω/km)	Inductance (H/km)	Capacitance (F/km)	Conductance (S/km)	Insertion loss (dB/km) (@ 135Ω)	Characteristic impedance (Ω)
BT_dw1	1 k	65.32	884.185e-6	48.707e-9	0.1479e-3	1.99	439.18
	10 k	65.56	883.094e-6	43.804e-9	0.8241e-3	2.47	172.90
	100 k	82.07	865.838e-6	40.064e-9	4.5916e-3	5.37	146.63
	1 M	228.65	813.038e-6	37.209e-9	25.5839e-3	23.14	147.45
	10 M	721.87	801.302e-6	35.031e-9	142.5496e-3	114.35	151.09
BT_dw3	1 k	265.83	1122.378e-6	46.288e-9	0.0363e-3	5.99	952.53
	10 k	275.49	975.219e-6	43.213e-9	0.2333e-3	6.42	321.81
	100 k	310.61	754.595e-6	40.572e-9	1.4980e-3	10.26	148.99
	1 M	356.27	712.065e-6	38.302e-9	9.6198e-3	17.04	136.51
	10 M	843.01	708.510e-6	36.351e-9	61.7749e-3	63.68	139.60
BT_dw5	1 k	258.00	1134.429e-6	43.925e-9	0.0186e-3	5.85	965.95
	10 k	266.64	1053.068e-6	40.611e-9	0.1545e-3	6.16	327.82
	100 k	305.80	821.487e-6	38.049e-9	1.2820e-3	9.50	158.30
	1 M	378.27	793.689e-6	36.067e-9	10.6383e-3	17.95	148.48
	10 M	996.75	792.793e-6	34.533e-9	88.2821e-3	86.69	151.47
BT_dw6	1 k	200.69	1098.399e-6	46.767e-9	0.0771e-3	4.90	813.02
	10 k	208.79	984.559e-6	42.660e-9	0.4616e-3	5.44	282.95
	100 k	243.64	786.121e-6	39.446e-9	2.7625e-3	9.00	148.61
	1 M	286.53	761.488e-6	36.932e-9	16.5311e-3	18.98	143.54
	10 M	689.78	760.321e-6	34.965e-9	98.9242e-3	83.67	147.40
BT_dw8	1 k	41.16	999.814e-6	37.456e-9	0.0231e-3	1.25	419.63
	10 k	41.59	997.166e-6	34.128e-9	0.1755e-3	1.37	186.96
	100 k	62.28	969.667e-6	31.549e-9	1.3313e-3	2.65	175.57
	1 M	186.92	920.407e-6	29.551e-9	10.0989e-3	12.50	176.40
	10 M	590.76	911.210e-6	28.003e-9	76.6083e-3	74.41	180.31
BT_dw10	1 k	180.93	727.591e-6	79.600e-9	0.0329e-3	4.49	600.91
	10 k	181.14	721.819e-6	72.887e-9	0.2365e-3	4.97	201.79
	100 k	199.02	694.785e-6	67.746e-9	1.6979e-3	9.13	106.12
	1 M	474.74	624.648e-6	63.808e-9	12.1890e-3	26.25	99.28
	10 M	1493.35	565.741e-6	60.793e-9	87.5047e-3	104.13	96.50
BT_dw12	1 k	55.47	619.920e-6	54.023e-9	0.0087e-3	1.63	404.67
	10 k	56.18	611.767e-6	53.424e-9	0.0662e-3	1.75	142.39
	100 k	87.79	565.329e-6	52.949e-9	0.5024e-3	3.93	104.87
	1 M	265.94	489.909e-6	52.573e-9	3.8109e-3	13.78	96.71
	10 M	840.58	465.757e-6	52.274e-9	28.9088e-3	50.80	94.41
BT_dwug	1 k	179.00	694.972e-6	55.501e-9	0.0006e-3	4.42	716.56
	10 k	179.16	694.564e-6	55.398e-9	0.0068e-3	4.57	230.16
	100 k	192.93	688.471e-6	55.316e-9	0.0731e-3	7.30	116.74
	1 M	438.33	640.000e-6	55.251e-9	0.7888e-3	18.13	107.94
	10 M	1376.49	591.529e-6	55.200e-9	8.5108e-3	61.72	103.55

***Table 24**: Simulation results, computed from the models of British cables, as specified in table 23.*

5.2. France (*France Telecom*)

Description of cables and network

The main cables of the France Telecom local network are identified as follows [12]:

- Branching cable : FT_DW1, FT_DW2, FT_DW3
- Distribution cable : FT_04 (0.4 mm), FT_06 (0.6 mm) and FT_08 (0.8 mm)

For branching cables, FT_DW1 and FT_DW2 cables are used only between an outside branching point and the subscriber house. The FT_DW3 is used when the branching point is inside a building and can be used also for the home wiring. The FT_DW1, is one pair flat cable (0.74 mm for diameter), and the FT_DW2 is a 2 pairs twisted cable (0.8 mm for the diameter), shielded or unshielded. These cables can be aerial or buried, the average length for the branching cable is around 50 m. The FT_DW3 is a quad twisted multipair cable, which can have up to 256 pairs, the diameter of the conductor is 0.6 mm, this cable is only wallmounted.

Concerning the distribution cables, they are all twisted quad multipair cable. In some cases, distribution cables with 0.5 mm and 0.9 mm can be found, but in a very small quantity. Their R, L, C, G parameters were not determined

Description of measurements

The principle of primary parameters measurements was based on measurements (with a network analyzer) of complex input reflections of the cable at one end while the other end is either in short circuit or in open circuit. The associated impedance values were extracted from these reflection measurements.

The measurements were split in two frequency bands, and were initially based on new cables [12]:

- for frequencies ranging from 10kHz to 1 MHz, the cables under test had a length of 2 m, and its input impedance have been measured directly using a network analyzer.
- for frequencies ranging from 1 MHz to 30 MHz, the input reflection (s_{11}, s_{22}) were measured on cable sections of 1.5 m and of 1m.

It was assumed that in this approach the length of the cable samples has to be much more shorter than the measurement wave length of interest ($L/\lambda << 0.1$, or even $L/\lambda << 0.01$). With shorter length the measurement results were considered as better at higher frequencies, because no reflection effect appeared on very short sections at high frequencies. This clarifies why the low frequency methods were restricted to 2 meter samples. For frequencies up to 20/30 MHz a cable length of 1.5 m or 1 m was considered as better.

Editorial note*: The requirement here to use very short cable sections is not a commonly used approach. Others have demonstrated [13,14, figure 8+9] and recommended[13] the use of very long sections (hundreds of meters or more) to average the random inhomogeneity in each meter. This long-section approach will minimize the scaling error when predicting cable properties of long sections based on measurements on short sections.*

Description of the models

Several typical cable samples were characterized, but it is unknown how good these samples can represent the entire French access network. The line constants for these cables samples are summarized in table 25, and are based on the BT#1 model, specified in table 10. They are valid up to 30MHz.

The extraction and fitting strategy was as follows. The parameters $\{Z_s, Y_p\}$ were extracted from a mix of these reflection/impedance measurements on short sections, and attenuation measurements on long sections (obtained from a previous campain over different cable lengths). Only three primary parameters $\{R_s, L_s, C_p\}$ have been averaged from the input reflection measurements that were averaged over different cable sections. The remaining conductance parameter $\{G_p\}$ was extracted from the attenuation measurements, by using the obtained $\{R_s, L_s, C_p\}$ values. If all four primary parameters would have been extracted from the short cable measurements, the predicted cable attenuation would not have fit very well with the measured attenuation on long cables.

Wire type	R_{oc} N_b	a_c g_0	R_{os} N_{ge}	a_s C_o	L_o C_∞	L_∞ N_{ce}	f_m
FT_dw1	37.795 0.716	0.079 9.097e-9	0.0 0.946	0.0 1.644e-7	1e-3 2.327e-8	0.84e-3 0.564	674800
FT_dw2	60.874 0.665	0.01 1.101e-8	0.0 1.014	0.0 1.288e-5	0.72e-3 4.642e-8	0.53e-3 0.924	327800
FT_dw3	118.719 0.805	0.026 9.4e-9	0.0 0.944	0.0 6.272e-6	0.61e-3 6.58e-8	0.41e-3 0.769	392600
FT_04	271.224 0.886	0.203 1.845e-14	0.0 1.57	0.0 6.365e-7	0.74e-3 4.93e-8	0.501e-3 0.599	607100
FT_06	122.577 0.786	0.044 3.033e-10	0.0 1.095	0.0 1.581e-6	0.72e-3 4.852e-8	0.48e-3 0.683	331600
FT_08	65.804 0.756	0.012 2.92e-7	0.0 0.606	0.0 8.998e-7	0.74e-3 4.479e-8	0.51e-3 0.626	180800

***Table 25**: Line constants for French cables, using the BT#1 model (see table 10)*

	Frequency (Hz)	**Resistance (Ω/km)**	**Inductance (H/km)**	**Capacitance (F/km)**	**Conductance (S/km)**	**Insertion loss (dB/km) (@ 135Ω)**	**Characteristic impedance (Ω)**
FT_dw1	1 k	38.16	998.506e-6	26.611e-9	0.0063e-3	1.15	480.73
	10 k	56.15	992.524e-6	24.182e-9	0.0553e-3	1.71	234.93
	100 k	167.76	967.504e-6	23.519e-9	0.4885e-3	4.20	206.52
	1 M	530.16	908.809e-6	23.338e-9	4.3142e-3	15.67	197.72
	10 M	1676.51	860.275e-6	23.289e-9	38.0977e-3	69.95	192.21
FT_dw2	1 k	60.89	716.049e-6	68.193e-9	0.0121e-3	1.78	377.40
	10 k	61.95	703.010e-6	49.014e-9	0.1253e-3	1.91	157.12
	100 k	103.27	660.668e-6	46.729e-9	1.2936e-3	4.41	120.64
	1 M	316.34	591.300e-6	46.457e-9	13.3594e-3	18.79	112.96
	10 M	1000.00	547.744e-6	46.424e-9	137.9708e-3	105.17	108.58
FT_dw3	1 k	118.72	608.381e-6	96.732e-9	0.0064e-3	3.18	442.07
	10 k	119.11	600.095e-6	71.065e-9	0.0561e-3	3.47	167.26
	100 k	146.34	560.087e-6	66.696e-9	0.4933e-3	7.12	95.36
	1 M	402.32	474.049e-6	65.953e-9	4.3364e-3	22.61	85.16
	10 M	1269.85	423.748e-6	65.826e-9	38.1178e-3	82.58	80.28
FT_04	1 k	271.23	739.185e-6	59.458e-9	0.0000e-3	6.04	852.13
	10 k	271.48	733.874e-6	51.857e-9	0.0000e-3	6.22	290.71
	100 k	293.71	699.783e-6	49.944e-9	0.0013e-3	10.08	129.81
	1 M	675.66	594.503e-6	49.462e-9	0.0485e-3	26.75	110.52
	10 M	2122.77	519.430e-6	49.341e-9	1.8030e-3	90.77	102.71
FT_06	1 k	122.58	717.520e-6	62.643e-9	0.0006e-3	3.25	558.26
	10 k	123.17	705.607e-6	51.450e-9	0.0073e-3	3.35	201.23
	100 k	160.63	652.692e-6	49.128e-9	0.0905e-3	5.93	119.45
	1 M	458.58	550.981e-6	48.646e-9	1.1269e-3	19.30	106.89
	10 M	1448.33	495.436e-6	48.546e-9	14.0240e-3	68.58	101.08
FT_08	1 k	65.81	735.566e-6	56.706e-9	0.0192e-3	1.91	430.01
	10 k	66.83	716.818e-6	47.609e-9	0.0775e-3	2.00	164.11
	100 k	108.53	650.322e-6	45.457e-9	0.3129e-3	4.05	121.66
	1 M	331.10	559.528e-6	44.948e-9	1.2629e-3	13.56	111.82
	10 M	1046.64	520.562e-6	44.827e-9	5.0978e-3	44.67	107.79

***Table 26**: Simulation results, computed from the models of French cables, as specified in table 25.*

5.3. Germany (*Deutsche Telekom AG*)

Description of cables and network

In the distribution part nearly all the cables are underground cables [11]. In some cases cables with a diameter of more than 0.6 mm can be found, but if the attenuation of these cables is smaller than the attenuation of the listed cables, those cables need not to be regarded. The table lists cables with 100 pairs only. Cables with other number of pairs are in use, but they have the same electrical characteristics. Cables with conductor diameters 0.40 mm and 0.60 mm have been deployed until 1993. Since 1993 only cables with a diameter of 0.35 mm or 0.50 mm have been used for new installations. While the 0.35 mm and 0.40 mm cables have a solid polyethylene isolation, the 0.50 mm and 0.60 mm cables are isolated by a polyethylene foam skin.

	cable type (code)	**conductor diameter**	**DTAG specification document number**
DTAG_35	A-2YF(L)2Y 100x2x0.35 StIII Bd	0.35 mm	FTZ TL 6145-3101
DTAG_40	A-2YF(L)2Y 100x2x0,40 StIII Bd	0.40 mm	FTZ TL 6145-3100
DTAG_50	A-2YSF(L)2Y 100x2x0,50 StIII Bd	0.50 mm	FTZ TL 6145-3101
DTAG_60	A-2YSF(L)2Y 100x2x0,60 StIII Bd	0.60 mm	FTZ TL 6145-3100

***Table 27**: Description of the construction of German cables*

Description of measurements

The parameters attenuation, phase coefficient and complex impedance have been measured with a combined spectrum/network analyser in the frequency range from 75 kHz to 30 MHz [21,11]. The method was the usual reflection factor measurement of a wire pair with open and short at the end of the pair (for γ_x and Z_0). NEXT and FEXT was measured in transmission mode.

Every parameter has been measured at 20 pairs of each cable. The measurement was carried out with cable rings of 100m length under laboratory conditions. For every conductor diameter cables of two different manufacturers have been examined, to cover different manufacturing processes.
First, the measured values of all measured wire pairs were averaged. Then a least-squared error fitting of the model was done. The models have been calculated individually for α, β, $re\{Z_0\}$ and $im\{Z_0\}$

Description of the models

The line constants for several German cables using the DTAG#1 model, specified in table 13, are summarized below. All single constants are valid within a frequency range of (75kHz .. 30 MHz). The three fold values for K_{a1}, K_{a2}, K_{a3} are valid within the succeeding ranges (0 .. 0.5MHz), (0.5 .. 5 MHz) and (5 .. 30 MHz) respectively. Below 75 kHz this model is invalid [11], except for $\gamma(f)$.
Table 29 summarizes the calculated results of the DTAG#1 model with the line constants of table 28. They are a little bit different from what was specified in [11], due to the limited accuracy of the parameters, due to the used approximation functions, and due to the use of a *clip*(x) function (see table 13) as an addition[7] to the original model of [11]. This difference is very small compared to the statistic variations from wire pair to wire pair.

[7] The difference in insertion loss between model and measurements has increased to about 0.5dB at 100 kHz for the DTAG_35 cable. This is a compromise between unrealistic negative conductance values or clipping the real part of Y_p.

	K_{a1}	K_{a2}	K_{a3}	K_{b1}	K_{b2}	K_{z1}	K_{z2}	K_{z3}	K_{x1}	K_{x2}	K_{x3}
DTAG_35	[9.4, 2.4, 15.9]	[13.2, 19.9, 11.2]	[0.97, 0.54, 0.69]	34.2	2.62	132	5.0	0.73	0.050	0.024	0.87
DTAG_40	[6.9, 0.3, 10.4]	[13.4, 18.9, 11.5]	[0.99, 0.50, 0.64]	32.9	2.26	127	8.8	0.51	0.045	0.016	0.81
DTAG_50	[4.2, 0.7, 10.3]	[11.9, 14.1, 7.7]	[0.92, 0.52, 0.68]	30.6	1.62	141	3.4	0.69	0.038	0.0082	0.73
DTAG_60	[2.4, 1.1, 8.7]	[11.2, 11.6, 6.6]	[0.75, 0.54, 0.69]	30.4	1.62	135	3.4	0.63	0.036	0.0038	0.64

Table 28*: Line constants for German cables, using the DTAG#1 model (see table 13)*

	Frequency (Hz)	Resistance (Ω/km)	Inductance (H/km)	Capacitance (F/km)	Conductance (S/km)	Insertion loss (dB/km) (@ 135Ω)	Characteristic impedance (Ω)
DTAG_35	100 k	392.71	928.520e-6	44.345e-9	0	11.10	158.87
	1 M	598.28	799.128e-6	42.869e-9	5.5593e-3	22.30	137.00
	10 M	1396.24	740.953e-6	41.944e-9	43.5425e-3	70.76	132.93
DTAG_40	100 k	301.81	898.206e-6	42.125e-9	0	8.62	155.50
	1 M	511.94	757.050e-6	41.281e-9	4.7631e-3	19.20	135.80
	10 M	1208.51	693.874e-6	41.247e-9	35.7449e-3	60.60	129.72
DTAG_50	100 k	208.14	848.601e-6	36.649e-9	0	5.84	157.66
	1 M	421.57	738.472e-6	35.558e-9	3.3650e-3	14.81	144.40
	10 M	1080.97	701.519e-6	34.950e-9	22.7855e-3	47.16	141.69
DTAG_60	100 k	155.87	816.923e-6	38.194e-9	0	4.58	149.51
	1 M	361.35	703.695e-6	36.858e-9	2.2509e-3	12.70	138.40
	10 M	987.49	667.993e-6	36.233e-9	16.0117e-3	41.03	135.80

Table 29*: Simulation results, computed from the models of German cables, as in table 28.*

5.4. The Netherlands (*KPN*)

Description of cables and network
The distribution network in the Netherlands is fully based on underground cables; aerial cables are not used [13]. The majority of these cables have 0.5mm wires but occasionally 0.8mm wires are used to reach longer distances. Dutch distribution cables are constructed in concentric layers, and each layer consist of a number of twisted quads, with a maximum of 450 quads per cable. A variety of distribution cables have been used during the past, but two dominant classes can be identified: "Norm 1" and "Norm 92" cables. Indoor cables ("Norm 88") are based on quads and 0.5mm wires too (massive copper).
A few cable samples have been measured, but at this moment it is not known how representative these samples are for the average Dutch network. The model for each sample is based on the average of the transfer of many wire pairs, in order to reduce the overall spread [13]. The samples of groundcables were extended with several meters indoor cable, and this extention was inevitable considered as part of the groundcable.

Sample name	*PTT-norm*	*Sample type*	*Sample length*	*description*
KPN_L1	N1 / GPLK	50×4×0.5mm	0.5 km	*groundcable, extended (few meters), paper insulated, lead shield*
KPN_L2	N1 / GPLK	150×4×0.5mm	1 km	*groundcable, extended (few meters), paper insulated, lead shield*
KPN_L3	N14 / GPLK	48×4×0.8mm	1.1 km	*groundcable, extended (few meters), paper insulated, lead shield*
KPN_L4	N1 / GPLK	150×4×0.5mm	1.5 km	*groundcable, extended (few meters), paper insulated, lead shield*
KPN_H1	N88	30×4×0.5mm	0.36 km	*indoorcable on a reel, polyethene insulated, unshielded*
KPN_KK	N88	1×4×0.5mm	36×0.2 km	*set of 36 indoorcables, polyethene insulated, unshielded*
KPN_R1	?	8×2×0.4mm	0.15 km	*Interrack cable, braided shield*
KPN_R2	?	1×4×0.5mm	0.44 km	*Interrack cable, Category 5, foil shield*
KPN_X1	?	2×0.5mm	0.2 km	*cross wire, unshielded*

Table 30*: Description of the construction of Dutch cables*

Description of measurements
All cables are characterized by full two-port s-parameter measurements using a (vector) network analyzer and balanced transformers (50Ω⇔150Ω). The frequency ranged from 1kHz to 30MHz. All systematic measurement errors, including transformer mis-match errors and connector errors, have been minimized by a full two-port calibration of the total setup. The reference planes (the 'interface' between measurement setup and the cable under test) were positioned directly at the cable input, by using a dedicated calibration set. Simple 'opens', 'shorts', 'loads' (constructed from small 150Ω resistors) and 'throughs' located at the reference planes have proven very effective for calibration purposes. Accurate positioning, (better than 5 mm) of the reference planes is relatively simple to obtain, when this approach is used.

The samples were taken as long as possible, preferably 1 km, in order to minimize the spread in loss of the (inhomogeneous) cables. At this length, the spread between the various wire pairs was observed to be less than 1 dB/km at 1MHz. Longer sections are prefered, but the maximum length is limited by the dynamic range of the measurement setup. Therefore the measured two-port s-parameters of the individual wire pairs were mathematically cascaded to tens of kilometers [13].
The models were extracted from this overall length, not from the individual sections. When models would have been extracted from sections of ten meters or less, and these short sections matched the average cable within 0.05dB/m, then *the error would have exploded to 50dB/km*!

Description of the models
Several typical cable samples were characterized, but it is unknown how good these samples can represent the entire Dutch access network. The line constants of these typical samples are summarized in table 31, using the KPN#1 model, specified in table 12. The models are validated from DC to 30

MHz, and describe the average of the cable samples. Errors due to scaling in length were proven to be less than the spread between the various wire pairs.
The fitting strategy for each cable was as follows: At first the spread between individual cable sections was averaged by a mathematical two-port cascade of all individual sections. Next, the parameters $\{Z_s, Y_p\}$ were extracted from this cascade, representing tens of kilometers in length. The fit for R_s was optimized at 'lower' frequencies, and for L_s at 'higher' frequencies, in order to model Z_s by Z_{sm}. The distinction between 'lower' and 'higher' is made by a changeover frequency where *real*(Z_s) equals *imag*(Z_s). Because Z_{sm} is an approximation of Z_s, parameter Y_p was adjusted to Y_{pp} in order to avoid cumulation of modelling errors. Its value was choosen to cause $Z_{sm}\cdot Y_{pp} \rightarrow \gamma^2$ for higher frequencies, and $Z_{sm}/Y_{pp} \rightarrow Z_0^2$ for lower frequencies. The fine-tuning constants were improved in an iterative way, to minimize the overall transmission error and to achieve a line constant M≡1.
The line constants are shown in table 31, and the associated simulation results in table 32.

	$Z_{0\infty}$	c/c_0	R_{ss00}	$2\pi\cdot\tan(\phi)$	K_f	K_l	K_n	K_c	N	f_{c0}	M
KPN_L1	136.651	0.79766	0.168145	0.13115	0.72	1.2	1	1.08258	0.7	4521710	1
KPN_L2	136.047	0.798958	0.168145	0.169998	0.7	1.1	1	1.08201	1	1862950	1
KPN_L3	137.527	0.850608	0.065682	0.114526	1	1	1	1.06967	1	559844	1
KPN_L4	137.005	0.787661	0.168145	0.153522	0.9	1	1	1.07478	1	557458	1
KPN_H1	135.458	0.640381	0.177728	0.018425	0.85	1	1	1.11367	1.5	5020	1
KPN_KK	142.451	0.712318	0.177728	0.071111	0.8	1.1	1	1.09373	0.5	8088	1
KPN_R1	87.7872	0.637656	0.2777	0.0963554	1.1	0.77	1	1.05036	1	3391970	1
KPN_R2	97.4969	0.639405	0.177728	0.0189898	0.5	1.14	1	1	1	100000	1
KPN_X1	110.538	0.629284	0.177728	0.0753736	1	0.97	1	1.1781	1	52284	1

Table 31: *Line constants for Dutch cables, using the KPN#1 model (see table 12)*

	Frequency (Hz)	**Resistance (Ω/km)**	**Inductance (H/km)**	**Capacitance (F/km)**	**Conductance (S/km)**	**Insertion loss (dB/km) (@ 135Ω)**	**Characteristic impedance (Ω)**
KPN_L1	1 k	168.15	784.381e-6	33.099e-9	0.0040e-3	4.21	899.29
	10 k	168.47	784.199e-6	33.072e-9	0.0401e-3	4.26	290.62
	100 k	197.37	768.161e-6	32.942e-9	0.4011e-3	5.77	158.71
	1 M	527.25	645.503e-6	32.454e-9	4.0107e-3	18.66	141.61
	10 M	1539.30	594.606e-6	31.501e-9	40.1067e-3	72.59	137.43
KPN_L2	1 k	168.15	763.156e-6	33.180e-9	0.0052e-3	4.21	898.12
	10 k	168.46	762.979e-6	33.168e-9	0.0521e-3	4.27	289.85
	100 k	195.52	747.534e-6	33.053e-9	0.5213e-3	5.86	156.49
	1 M	494.07	634.901e-6	32.303e-9	5.2133e-3	18.46	140.71
	10 M	1408.83	588.893e-6	31.062e-9	52.1326e-3	75.61	137.72
KPN_L3	1 k	65.69	716.709e-6	30.476e-9	0.0033e-3	1.89	586.34
	10 k	66.19	716.194e-6	30.445e-9	0.0326e-3	1.93	204.53
	100 k	101.18	681.040e-6	30.179e-9	0.3263e-3	3.11	152.27
	1 M	303.71	584.661e-6	29.207e-9	3.2634e-3	11.33	141.71
	10 M	924.93	553.395e-6	28.600e-9	32.6336e-3	48.59	139.12
KPN_L4	1 k	168.15	757.574e-6	33.195e-9	0.0047e-3	4.21	897.95
	10 k	168.36	757.476e-6	33.158e-9	0.0474e-3	4.26	289.76
	100 k	188.46	748.530e-6	32.847e-9	0.4742e-3	5.62	156.66
	1 M	491.19	649.149e-6	31.716e-9	4.7421e-3	17.84	143.56
	10 M	1433.66	601.744e-6	31.011e-9	47.4213e-3	73.39	139.33
KPN_H1	1 k	177.73	882.867e-6	42.438e-9	0.0007e-3	4.39	816.61
	10 k	177.95	882.770e-6	39.573e-9	0.0071e-3	4.42	273.79
	100 k	198.07	873.795e-6	38.476e-9	0.0708e-3	5.67	155.38
	1 M	500.59	774.383e-6	38.428e-9	0.7080e-3	15.73	142.33
	10 M	1442.25	727.019e-6	38.427e-9	7.0803e-3	49.76	137.58
KPN_KK	1 k	177.73	862.162e-6	35.128e-9	0.0023e-3	4.40	897.53
	10 k	177.99	862.041e-6	34.308e-9	0.0234e-3	4.43	293.77
	100 k	201.27	851.013e-6	33.532e-9	0.2336e-3	5.60	164.67
	1 M	525.70	740.552e-6	33.104e-9	2.3360e-3	16.78	150.04
	10 M	1530.78	690.009e-6	32.935e-9	23.3601e-3	60.62	144.78

Table 32: *Simulation results, computed from the models of Dutch cables, as specified in table 31.*

5.5. Finland and Baltic countries (*Nokia*)

Note that the information in this paragraph is provided by the cable manufacturer Nokia, and that this information is not confirmed, nor disputed, by the associated operators.

Description of cables and network

The most common types of cables used in Finland [15] have 0.4 or 0.5 mm diameter copper conductors, polyethene insulated conductors, plastic aluminium laminate strength member and polyethene sheath. These cables are manufactured by Nokia Cables and also widely used in the Baltic countries Estonia, Latvia and Lithuania.

	Cable type (Nokia code)	conductor diameter
NOK_40	VMOHBU 04	0.4 mm
NOK_50	VMOHBU 05	0.5 mm

A description of the metallic access network can be given by Finnish telecommunications operators.

Description of measurements

The primary cable parameters that are used to model these cables are design targets, ***not measured*** values. The information has been provided by Nokia Cables [15]
One target in Nokia cables is to have constant capacitance value. Because of that C_0 and N_{ce} are zeroes.

Description of the models

The line constants are presented in table 33, using the curve fitting functions of the BT#1 model, as specified in table 10. They are valid up to 30 MHz. The associated simulation results are summarized in table 34.

Wire type	R_{oc} / N_b	a_c / g_0	R_{os} / N_{ge}	a_s / C_o	L_o / C_∞	L_∞ / N_{ce}	f_m
NOK_40	271.9983	0.07960468	0	0	710.7494e-6	590.0163e-6	1.0300517e6
	1.229532	1.100869e-9	0.999424	0	38.6e-9	0	
NOK_50	173.99847	0.0322326	0	0	707.45088e-6	581.5551e-6	693.804e3
	1.095304	0.5007629e-9	1.04681	0	38.9e-9	0	

Table 33: *Line constants for Nokia cables, using the BT#1 model (see table 10)*

	Frequency (Hz)	Resistance (Ω/km)	Inductance (H/km)	Capacitance (F/km)	Conductance (S/km)	Insertion loss (dB/km) (@ 135Ω)	Characteristic impedance (Ω)
NOK_40	1 k	272.00	710.726e-6	38.600e-9	0.0011e-3	6.05	1059.08
	10 k	272.10	710.346e-6	38.600e-9	0.0110e-3	6.14	337.18
	100 k	281.39	704.256e-6	38.600e-9	0.1094e-3	8.59	147.04
	1 M	540.08	651.482e-6	38.600e-9	1.0921e-3	18.63	130.48
	10 M	1680.00	596.972e-6	38.600e-9	10.9070e-3	64.56	124.42
NOK_50	1 k	174.00	707.354e-6	38.900e-9	0.0007e-3	4.32	843.88
	10 k	174.15	706.251e-6	38.900e-9	0.0077e-3	4.37	271.16
	100 k	187.61	693.978e-6	38.900e-9	0.0858e-3	5.96	139.36
	1 M	426.70	632.066e-6	38.900e-9	0.9561e-3	15.05	127.84
	10 M	1340.00	587.983e-6	38.900e-9	10.6488e-3	53.03	122.98

Table 34: *Simulation results, computed from Nokia cables, as specified in table 33.*

5.6. Switzerland (*Swisscom*)

Description of cables and network

The most common type of cables used in Switzerland have 0.4 mm and 0.6 mm diameter copper conductor [17]. The cable structure may differ significantly: paper, PVC or PEZ isolation. Dispite the different structures of the access network cables, the models below apply to most of them.

Description of measurements

The primary parameters of the cables have beeen determined from s-parameter measurements performed on various cable sections, ranging from 100 - 500m.

Description of the models

The line constants are presented in table 33, using the curve fitting functions of the BT#1 model, as specified in table 10. They are valid up to 30 MHz, for frequency domain simulations over a wide frequency range. The associated simulation results are summarized in table 34.
Simulations and table 34 illustrate that L_s and C_p become unrealistic below about 3 kHz, and that the conductance G_p is unrealistic (negative) for most frequencies. This limits the application of the model, especially for time domain simulations. The negative G_p indicates that the predicted R_s is (above about 1 MHz) probably higher than the real one.

	Z_{00}	f_1	f_2	f_3	f_4	f_5	N_{e1}	N_{e2}	N_{e3}	N_{e4}	C_1	C_2	C_3
SWC_40	135	45000	44000	13000	250000	24500	0.59	0.65	0.475	0.51	0.44	0.007	0.043
SWC_60	135	13000	21000	7500	125000	12500	0.75	0.65	0.475	0.51	0.46	0.0037	0.022

***Table 35**: Line constants for Swisscom cables, using the SWC#1 model (see table 14)*

	Frequency (Hz)	Resistance (Ω/km)	Inductance (H/km)	Capacitance (F/km)	Conductance (S/km)	Insertion loss (dB/km) (@ 135Ω)	Characteristic impedance (Ω)
SWC_40	1 k	285.78	3694.660e-6	27.274e-9	-0.0105e-3	6.26	1292.29
	10 k	273.97	859.060e-6	32.621e-9	0.0044e-3	6.11	369.10
	100 k	303.76	795.458e-6	32.945e-9	-0.1481e-3	8.01	168.09
	1 M	773.86	637.006e-6	33.776e-9	-7.6854e-3	19.73	138.55
	10 M	4855.68	599.106e-6	32.902e-9	-132.6609e-3	78.15	135.36
SWC_60	1 k	156.49	2060.066e-6	26.157e-9	-0.0064e-3	3.97	977.08
	10 k	130.10	877.899e-6	35.377e-9	0.0175e-3	3.43	252.13
	100 k	160.65	713.199e-6	34.595e-9	0.6114e-3	5.15	147.96
	1 M	526.18	623.567e-6	33.857e-9	-2.4424e-3	15.35	136.31
	10 M	3394.45	595.763e-6	32.737e-9	-76.4743e-3	64.33	135.13

***Table 36**: Simulation results, computed from Swisscom cables, as specified in table 35.*

5.7. Cables, as used in ANSI testloops

The ANSI (T1E1.4) report on VDSL systems requirments characterized four cables for test purposes.

- ANSI_TP1 is representative of a 0.4 mm, or 26-gauge, phone-line twisted pair cable. The specific cable was provided by Bell South to BT and measurements were validated by GTE to produce an acceptable fit between measured responses and projected insertion loss.
- ANSI_TP2 is representative of 0.5 mm, or 24-gauge, phone-line twisted pair.
- ANSI_TP3 is a 0.5 mm copper PVC-insulated conductors, PVC-insulated steel strength member, polyethylene sheath. It is identical to cable BT_DW10 (see table 22)
- ANSI_FP is a 1.14 mm flat (no twists) phone-line. It is identical to cable BT_DW8 (see table 22).

The line constants are summarized in table 37, and some computed line parameters in table [*]

Wire type	R_{oc} / N_b	a_c / g_0	R_{os} / N_{ge}	a_s / C_o	L_o / C_∞	L_∞ / N_{ce}	f_m
ANSI_TP1	286.17578 0.92930728	0.14769620 43e-9	∞ 0.70	0 0	675.36888e-6 49e-9	488.95186e-6 0	806338.63
ANSI_TP2	174.55888 1.1529766	0.053073481 **234.87476e-15**	∞ 1.38	0 0	617.29539e-6 50e-9	478.97099e-6 0	553760
ANSI_TP3	180.93 0.75577086	49.7223e-3 89e-9	∞ 0.856	0.0 63.8e-9	728.87e-6 51e-9	543.43e-6 0.11584622	718888
ANSI_FP	41.16 1.195	1.218e-3 53e-9	∞ 0.88	0.0 31.78e-9	1e-3 22.68e-9	910.505e-6 0.1109	174877

***Table 37**: Line constants for American cables (according to the ANSI VDSL report [*]), using the BT#1 model (see table 10)*

	Frequency (Hz)	Resistance (Ω/km)	Inductance (H/km)	Capacitance (F/km)	Conductance (S/km)	Insertion loss (dB/km) (@ 135Ω)	Characteristic impedance (Ω)
ANSI_TP1	1 k	286.18	674.999e-6	49.000e-9	0.0054e-3	6.28	964.10
	10 k	286.33	672.268e-6	49.000e-9	0.0271e-3	6.48	306.60
	100 k	300.77	651.941e-6	49.000e-9	0.1360e-3	10.56	128.48
	1 M	626.85	572.869e-6	49.000e-9	0.6815e-3	25.49	108.94
	10 M	1960.61	505.334e-6	49.000e-9	3.4156e-3	85.49	101.65
ANSI_TP2	1 k	174.56	617.200e-6	50.000e-9	0.0000e-3	4.33	745.51
	10 k	174.81	615.957e-6	50.000e-9	0.0001e-3	4.46	238.73
	100 k	195.45	600.416e-6	50.000e-9	0.0019e-3	7.43	116.29
	1 M	482.06	525.440e-6	50.000e-9	0.0448e-3	20.53	103.05
	10 M	1517.88	483.722e-6	50.000e-9	1.0736e-3	67.67	98.42
ANSI_TP3	1 k	180.93	727.593e-6	79.660e-9	0.0329e-3	4.49	600.69
	10 k	181.14	721.820e-6	72.950e-9	0.2363e-3	4.97	201.71
	100 k	199.02	694.785e-6	67.811e-9	1.6959e-3	9.14	106.07
	1 M	474.74	624.645e-6	63.875e-9	12.1728e-3	26.25	99.23
	10 M	1493.35	565.737e-6	60.860e-9	87.3756e-3	104.09	96.44
ANSI_FP	1 k	41.16	999.813e-6	37.452e-9	0.0231e-3	1.25	419.65
	10 k	41.59	997.164e-6	34.123e-9	0.1755e-3	1.37	186.97
	100 k	62.29	969.664e-6	31.544e-9	1.3313e-3	2.65	175.59
	1 M	186.92	920.411e-6	29.547e-9	10.0989e-3	12.50	176.41
	10 M	590.76	911.210e-6	27.999e-9	76.6083e-3	74.41	180.32

***Table 38**: Simulation results, computed from the models of ANSI cables, as specified in table 37.*

6. Crosstalk line constants for various access cables

editorial notes:
Very little seems to be known about crosstalk modeling, compared to the knowledge on two-port modeling. A systematic overview on the crosstalk in various different European cables is lacking. I would like to have more input on these topics, to bring this paragraph alive. Can anybody help me with references (ETSI as well as public) or copies of relevant articles on these issues?
I have at least the following questions / concerns:

(a) I am not aware of an experimental proof that the EL-FEXT scales proportionally to the root of the cablelength, or $10\cdot{}^{10}\log(x)$ *on a dB scale. Until now, I have received the following valuable comments, including:*

- *The Berlin contribution TD14 (972T14A0) comments that DTAG has observed that the measured length dependency of FEXT is in accordance with the commonly used length dependency. The results have not been published yet.*
- *In private communications with NKF (one of the Dutch cable manufacturer), I was told that NKF has observed (after extensive investigations) an EL-FEXT scaling of* $15\cdot{}^{10}\log(x)$ *while* $10\cdot{}^{10}\log(x)$ *is expected from theory.*

These two seem to be conflicting statements on FEXT, and illustrate the relevance on more input.

(b) The same applies to the overall crosstalk generated by N interferers. (N>>1). I am not aware of an experimental proof on the reliability of the power-sum scaling function Φ(N).

(c) Focussing all crosstalk modelling on cables alone might be insufficient for VDSL range calculations. In practice the crosstalk in splices and the main distribution frame (MDF) may play a significant role too. So far, I have not seen any VDSL range estimation, that has taken account for these effects. Based on that, I have the feeling that this is a generally ignored aspect.! Please correct me if I am wrong on this.

6.1. Cables as used in ETSI and ANSI technical reports

Some crosstalk constants are commonly used in simulations and performance tests [4,5]. They are considered as a average for many cables. The commonly used constants are summarized in table 39 and 40. In all case, a normalized power-sum scaling function of $\Phi(N) = N^{K_m}$ is assumed. The predicted values should represent the 1% worst-case NEXT and FEXT disturbers.
Note that different constants are reported too [21, 22, 23,24]. In [23] a difference of more than 7 dB was observed for a German cable sample.

Crosstalk Model[8] X#0	K_m	K_{xn}	K_{xf}	K_w	K_L	x_0	$\omega_0/2\pi$
ANSI/ADSL [4]	0.3	$9.39\cdot10^{-8}$	$1.97\cdot10^{-10}$	0.75	0.5	1 m	1 Hz
ANSI/VDSL [5]	0.3	$9.84\cdot10^{-8}$	$1.69\cdot10^{-10}$	0.75	0.5	1 m	1 Hz
BT [20]	0.3	$9.84\cdot10^{-8}$	$1.59\cdot10^{-10}$	0.75	0.5	1 m	1 Hz

[8] These values are extracted from the ANSI standards [4,5], by
ANSI/ADSL: $K_{xn} = \sqrt{0.882\cdot10^{-14}}$, $K_{xf} = \sqrt{(10/49)^{0.6}\cdot 3.083\cdot10^{-20} / 0.3048}$
ANSI/VDSL: $K_{xn} = \sqrt{(1/49)^{0.6}\cdot 10^{-13}}$, $K_{xf} = \sqrt{(1/49)^{0.6}\cdot 9\cdot10^{-20} / 0.3048}$

***Table 39**: Some average constants for crosstalk model "X#0", valid only when N>>1*

Crostalk Model X#2	K_m	C_{xn}	C_{xf}	K_w	K_L	x_0	$\omega_0/2\pi$	R_N
ANSI/ADSL [4]	0.3	7.0 pF	0.466pF/√m	0.75	0.5	1 m	1 MHz	135 Ω
ANSI/VDSL [5]	0.3	7.34 pF	0.398pF/√m	0.75	0.5	1 m	1 MHz	135 Ω
BT [20]	0.3	7.34 pF	0.376pF/√m	0.75	0.5	1 m	1 MHz	135 Ω

***Table 40**: Some average constants for crosstalk model "X#2", valid only when N>>1*

	Frequency (Hz)	**NEXT (dB) @ 1 km**	**EL-FEXT (dB) @ 0.3 km**	**EL-FEXT (dB) @ 1 km**	**EL-FEXT (dB) @ 3 km**
ANSI - ADSL	10 k 100 k 1 M 10 M				
ANSI - VDSL	10 k 100 k 1 M 10 M				

7. Unbalance constants for various access cables

7.1. Germany *(Deutsche Telekom AG)*

Model LCL#1 have proven to be adequate to approximate the cable unbalance of German cables [18]. These observations are based on 120 measurements (20 pairs per cable), and cable samples of 100 m. Table 41 summarizes typical unbalance constants:

cable	f_0	K_{u1}	K_{u2}
average case	1 MHz	52.9	9.8
worst case	1 MHz	42.9	9.8

***Table 41**: LCL constants for the unbalance of German cables, using the LCL#1 model (see table19)*

7.2. France *(France Telecom)*

Model LCL#3 have proven to be adequate to approximate the cable unbalance of French cables [19]. In practice, there is some discrepancy between these models and the measurements.
Table 42 summarizes typical unbalance constants:

cable	f_0	K_{ua}	K_{ub}	K_{uc}	K_{ud}
FT_FTP5	1 MHz	1.8770	-0.0170	-0.1500	-0.1260
FT_FTP4	1 MHz	1.9080	-0.0170	-0.1470	-0.0670
FT_UTP5	1 MHz	1.9920	-0.0200	-0.1860	-0.3280
FT_DW1	1 MHz	1.9300	-0.0570	-0.4490	-0.3450
FT_DW2	1 MHz	1.9445	-0.0128	-0.1452	-0.0808
FT_DW3	1 MHz	1.9640	-0.0180	-0.1940	-0.1320

***Table 42**: LCL constants for the unbalance of French cables, using the LCL#3 model (see table19)*

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8.2. Addresses

For technical discussions and questions on various cable models:

Contact BT:	Kevin T. Foster BT Laboratories Martlesham Heath Ipswich Suffolk England	Tel: +44 1473 642986 Fax: +44 1473 614580 Email: fosterkt@boat.bt.co.uk
Contact DTAG:	Andreas Ehre Deutsche Telekom AG Technologiezentrum Postfach 10 00 03 D-64276 Darmstadt Germany	Tel: +49 6151 83 4752 Fax: +49 6151 83 2256 Email: ehre@tzd.telekom.de
Contact FT:	Marc Vautier CNET/LAB/RSD/DVS 2, Avenue Pierre Marzin BP40, 22300 Lannion France	Tel : 33 96 05 24 83 Fax : 33 96 05 22 94 E mail : vautier@lannion.cnet.fr
Contact KPN:	Rob.F.M. van den Brink KPN Research PO Box 421 2260 AK Leidschendam The Netherlands	Tel: +31 70 3325389 Fax: +31 70 3326477 Email: R.F.M.vandenBrink@research.kpn.com
Contact NOKIA:	Jari Lindholm Nokia Telecommunications, P.O.BOX 370, FIN-00045 Nokia Group, Finland	Tel: +358 9 5112 0562 Fax: +358 9 5112 0863 Email: jari.lindholm@ntc.nokia.com
Contact Swisscom:	Marcos Rubinstein Swisscom Ostermundigenstrasse 93 3000 Bern 29 Switzerland	Tel: +41 31 3424934 Fax: +41 31 3426424 Email: marcos.rubinstein@swisscom.com