SOURCE: KPN (PTT Telecom, KPN Research)
author: Rob van den Brink

CONTACT R.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

TITLE **VDSL - Measurements and models on Dutch cables**

STATUS For information.

ABSTRACT This contribution provides measurements and simulation models on cables that are in use in the Dutch access network. The network is described in short and a new cable model is introduced. The model constants are extracted from measurements on very long cables (up to 1500m) to minimize errors caused by spread in 'equal' sections.

1. Description of cables and network

The distribution network in the Netherlands is fully based on underground cables; aerial cables are not in use. 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 several 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 also based on quads and 0.5mm wires.
A few cable samples have been measured, as described in table 1, but at this moment it is not known how representative these samples are for the average Dutch network. The model for each sample is extracted from the average characteristics of many wire pairs, in order to reduce the overall spread. 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	?	50×4×0.5mm	0.5 km	*groundcable, extended with norm 88*
KPN_L2	?	150×4×0.5mm	1 km	*groundcable, extended with norm 88*
KPN_L3	?	48×4×0.8mm	1.1 km	*groundcable, extended with norm 88*
KPN_L4	?	150×4×0.5mm	1.5 km	*groundcable, extended with norm 88*
KPN_H1	88	30×4×0.5mm	0.36 km	*indoorcable on a reel*
KPN_KK	88	1×4×0.5mm	36×0.2 km	*set of 36 indoorcables*

Table1*: Description of the samples of Dutch cables*

2. 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 eliminated by a full two-port calibration of the total setup [3]. 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 [3]. Accurate positioning, (better than 5 mm) of the reference planes is relatively simple to obtain, when this approach is used.

2.1. Measurement results on transmission s_{21}

Twisted pair cables are a slightly inhomogeneous in nature, which causes some spread in the cable characteristics per unit length. In order to average this spread, the samples were taken as long as possible, preferably 1 km. At this length, the spread at 1MHz between the individual wire pairs in a cable was observed to be less than 1 dB/km. Longer sections are prefered, but the maximum length is limited by the dynamic range of the measurement setup. Figure 1, 2 and 3 show the measured transfer of several wire pairs in the cable samples.
The dynamic range of transmission measurements on very long cables (figure 1and 2) was limited above 10 MHz by crosstalk in the setup (connectors, connection cables, etc). Meanwhile, we have solved this by using shielded connection cables (twisted pair) and other connectors.

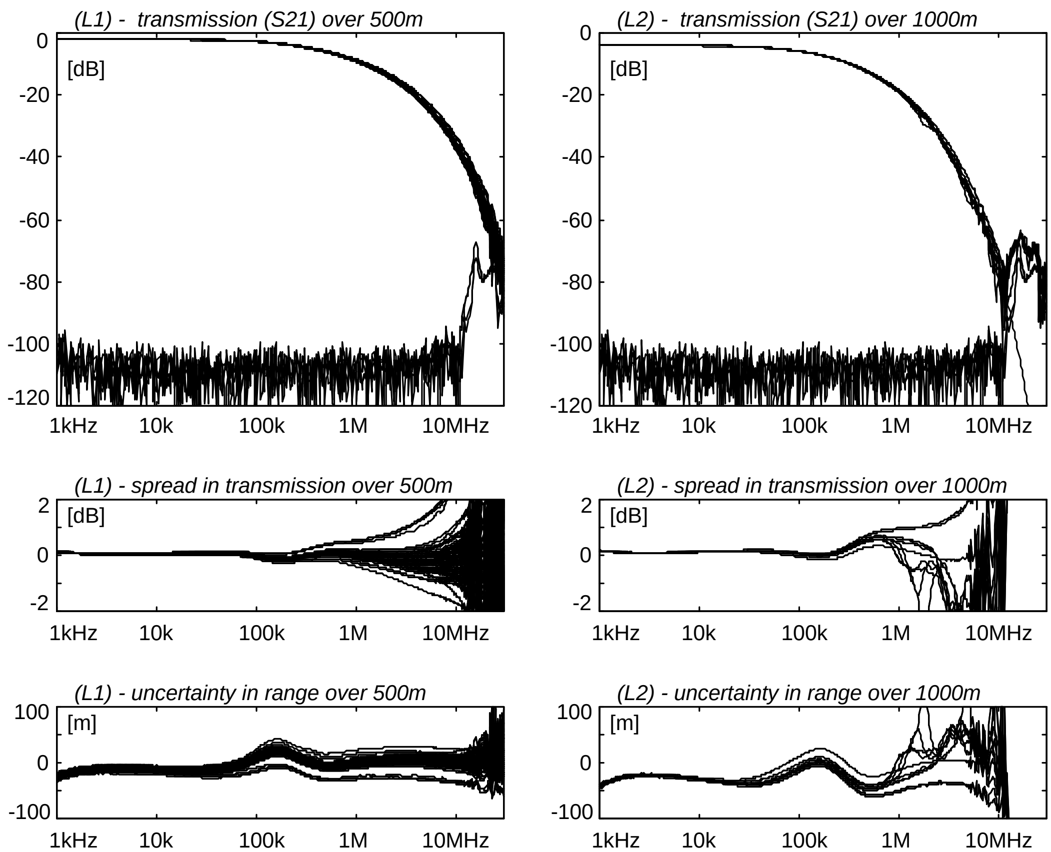

***Figure 1**. Measured transmission (s_{21}, s_{12}) of buried cables, normalized to 150W, as a function of the frequency. The KPN_L1 plot shows 60 wire pairs (0.5mm),and the KPN_L2 plot 10 wire pairs (0.5mm). The average cable length is estimated at L1=496m and L2=1040m, based on the total loopresistance.*

The measured curves in figure 1, 2 and 3 are overlayed with simulated curves, based on models of the average cables, as summarized in table 4. The companion plots in figures 1, 2 and 3 illustrate the spread in overall transmission (compared to this averaged model) and the uncertainty in length due to this spread. The associated quantities are defined as:

transmission spread (at length *x*): $\frac{|s_{21}|}{|s_{21o}|}$

length uncertainty (at length *x*): $\frac{\log(|s_{21}| / |s_{21o}|)}{\log(|s_{21o}|)} \cdot x$

Length uncertainty is a quantity that indicates the expected error when length is estimated at a specified frequency from insertion loss.

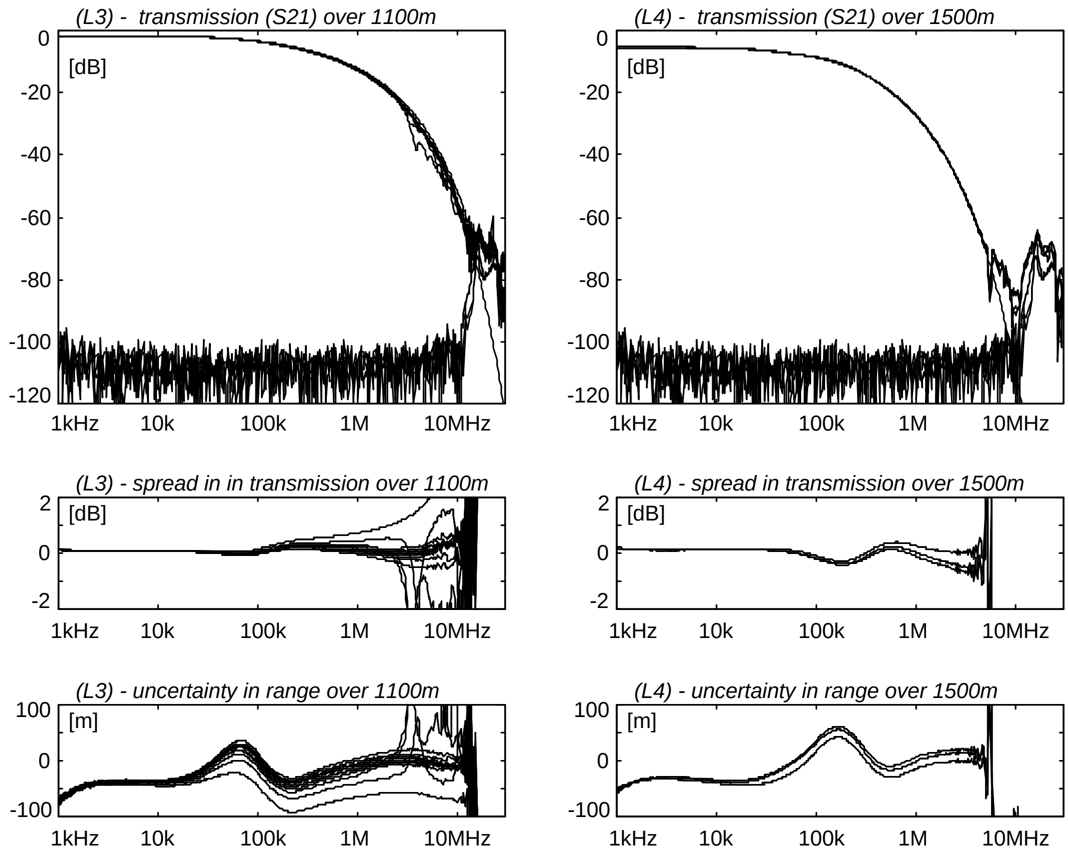

***Figure 2**. Measured transmission (s_{21}, s_{12}) of buried cables, normalized to 150W, as a function of the frequency. The KPN_L3 plot shows 13 wire pairs (0.8mm), and the KPN_L4 plot 3 wire pairs (0.5mm). The average cable length is estimated at L3=1140m and L4=1540m, based on the total loop resistance.*

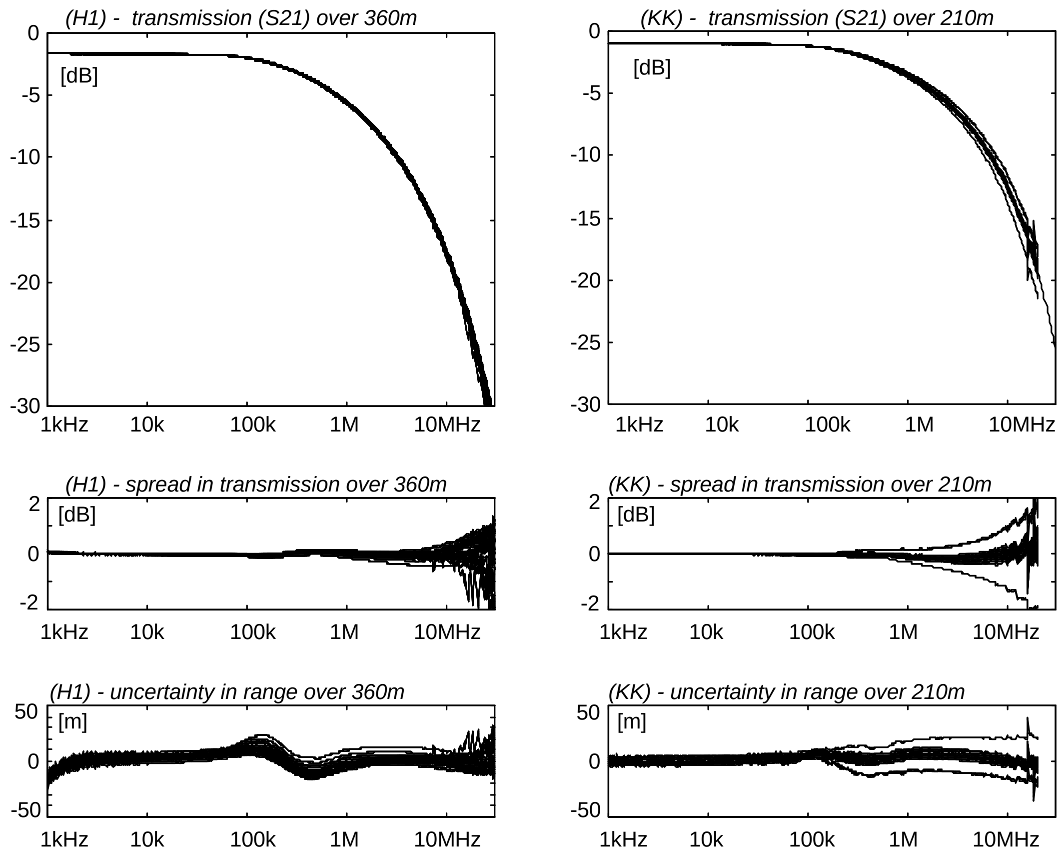

***Figure 3**. Measured transmission* (s_{21}, s_{12}) *of in-door cables, normalized to 150W, as a function of the frequency. The KPN_H1 plot shows 60 wire pairs (0.5mm), and the KPN_KK plot 24 wire pairs (0.5mm). The average cable length is estimated at H1=357m and KK=208m, based on the total loopresistance.*

2.2. Measurement results on characteristic impedance Z_0

The characteristic impedance Z_0 is the geometric average of the two image impedances Z_{01} and Z_{02}. In a homogeneous cable these two image impedances are equal, but in practice they are different.

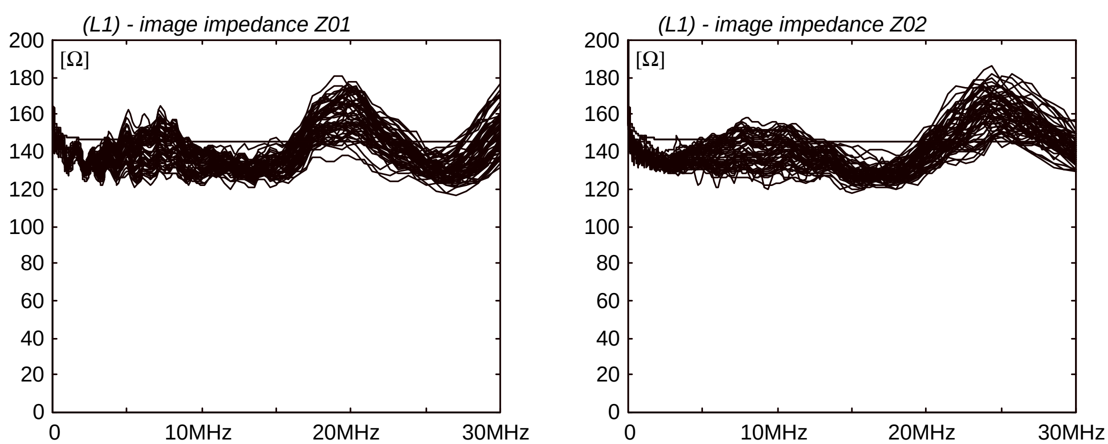

***Figure 4**. Measured image impedance* (Z_{01}, Z_{02})*, on the two sides of the KPN_L1 burried cable (500m, 50 ´4 ´0.5mm), based on 60 individual wire pair measurements. The short (unidentified) indoor extention cable interferes with these measurements.*

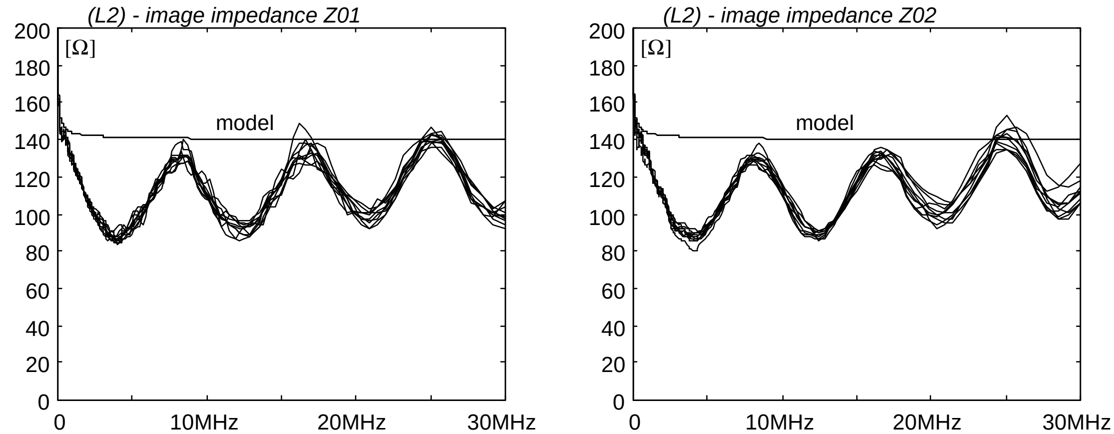

Figure 5*. Measured image impedance* (Z_{01}, Z_{02})*, on the two sides of the KPN_L2 burried cable (1000m, 150 ´4 ´0.5mm), based on 10 individual wire pair measurements. The short (unidentified) indoor extention cable interferes with these measurements.*

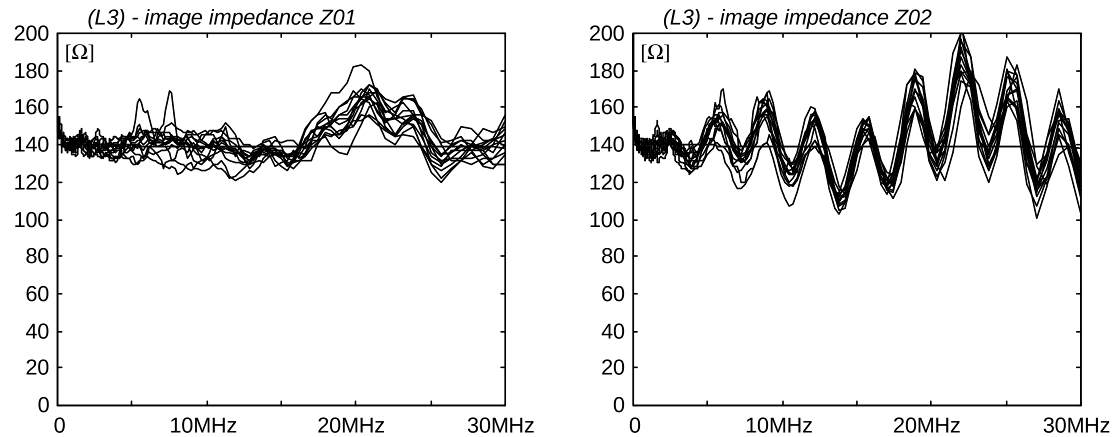

Figure 6*. Measured image impedance* (Z_{01}, Z_{02})*, on the two sides of the KPN_L3 burried cable (1100m, 48 ´4 ´0.8mm), based on 13 individual wire pair measurements. The short (unidentified) indoor extention cable interferes with these measurements.*

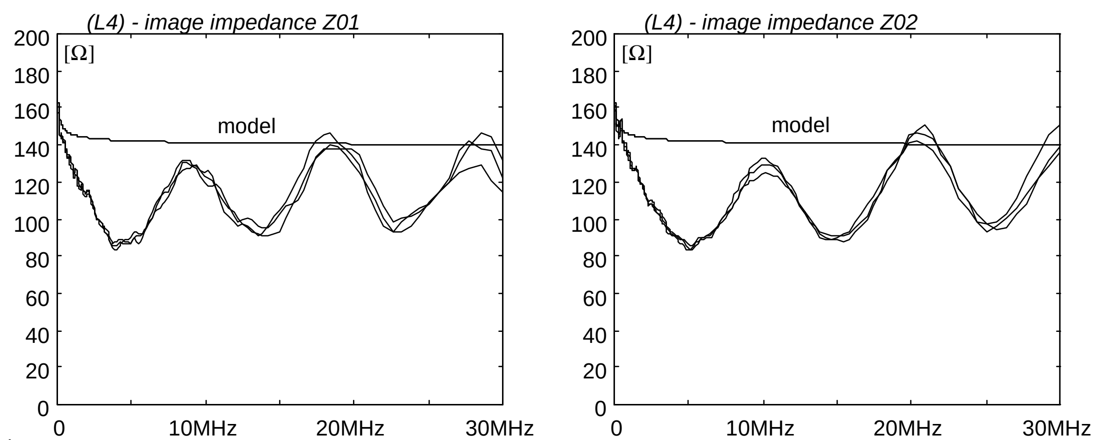

Figure 7*. Measured image impedance* (Z_{01}, Z_{02})*, on the two sides of the KPN_L4 burried cable (1500m, 150 ´4 ´0.8mm), based on 3 individual wire pair measurements. The short (unidentified) indoor extention cable interferes with these measurements.*

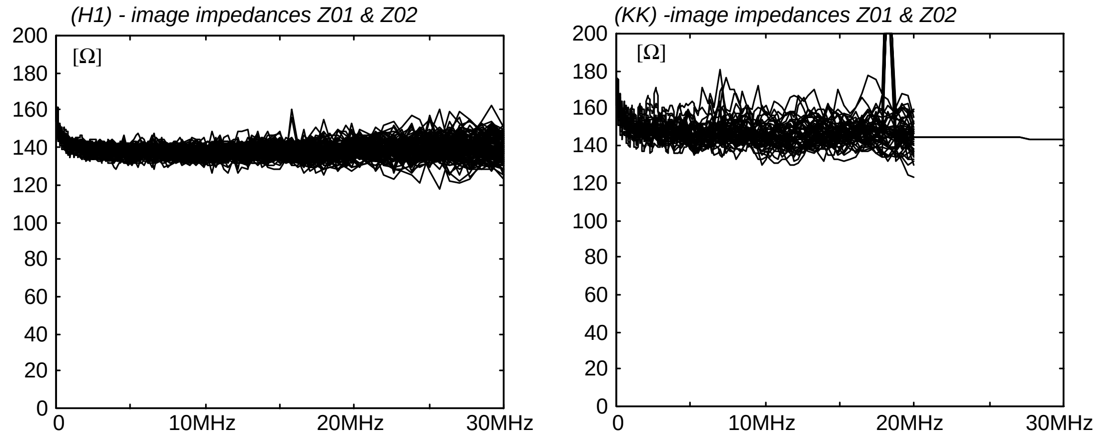

Figure 8. *Measured image impedances* (Z_{01}, Z_{02}), *on both sides of the KPN_H1 (360m, 30 ´4 ´0.5mm) and KPN_KK (200m, 1 ´4 ´0.5mm) indoorcables, based on 60 and 24 individual wire pair measurements. The lack of an extention cable improves the overall flatness of the individual curves.*

Figures 4, 5, 6, 7 and 8 illustrate the image impedances of various individual wire pairs, overlaid by the calculated value from the associated models. The burried cables are extended with several meters (unidentified) indoor cables, having a deviant characteristic impedance. The reflections in this extention cable causes the image impedances of the combination to be frequency dependent. Since the extention length was different for all cable ends, the image impedances are different too.
The average model was fit to the two-port parameters as if the extention cables were absent.

3. Modelling

3.1. The KPN two-port model

The empirical models KPN#0 and KPN#1 of the Royal PTT Netherland, are modelling $\{Z_s, Y_p\}$. These models are significantly different from the BT#1 and the DTAG#1 model [1,2,4] 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 specified in table 2 and 3 and are able to predict the cable characteristics from DC to tens of MHz.

$Z_{s0}(\omega) = j\cdot\omega\cdot Z_{0\infty} / c \;+\; R_{ss00}\cdot(1/4 \;+\; \chi\cdot\coth(4/3\cdot\chi))$	[Ω/m]
$Y_{p0}(\omega) = j\cdot\omega/Z_{0\infty} / c \;+\; (\tan(\phi)/Z_{0\infty})/c\cdot\omega$	[S/m]

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

Table 2*: Simplified "KPN#0" model, based on four line constants, to describe the dominant behavior of cables. In these expressions* $m_0=4\cdot p\cdot 10^{-7}$ *[H/m] represents the permeability of vacuum, and c the propagation speed (lower than the speed of light* $c_0=3\cdot 10^8$ *[m/s]). The asymptotic series inductance and shunt capacitance are equal to* $L_{s\infty} = Z_{0\infty}/c$ *en* $C_{p\infty}=1/(c\cdot Z_{0\infty})$.

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

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

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

***Table 3**: The formal "KPN#1" mode 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.*

3.2. The actual models of the cable sections

The line constants for several Dutch cables associated with the KPN#1 model (see table 3), are summarized in table 4. 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.
Figure 9 illustrates the simulated transfer, representing the average of the cable samples, and scaled to 1 kilometer. Table 5 summarizes some simulated cable characteristics at three sample frequencies.

	Z0¥	c/c_0	R_{ss00}	2p·tan(f)	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

***Table 4**: Line constants for Dutch cables, using the KPN#1 model (see table 3)*

	Frequency (Hz)	Resistance (W/km)	Inductance (H/km)	Capacitance (F/km)	Conductance (S/km)	Insertion loss (dB/km) (@ 135W)	Characteristic impedance (W)
KPN_L1	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	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	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	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	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	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 5**: Simulation results, based on the models of Dutch cables, in table **4**.*

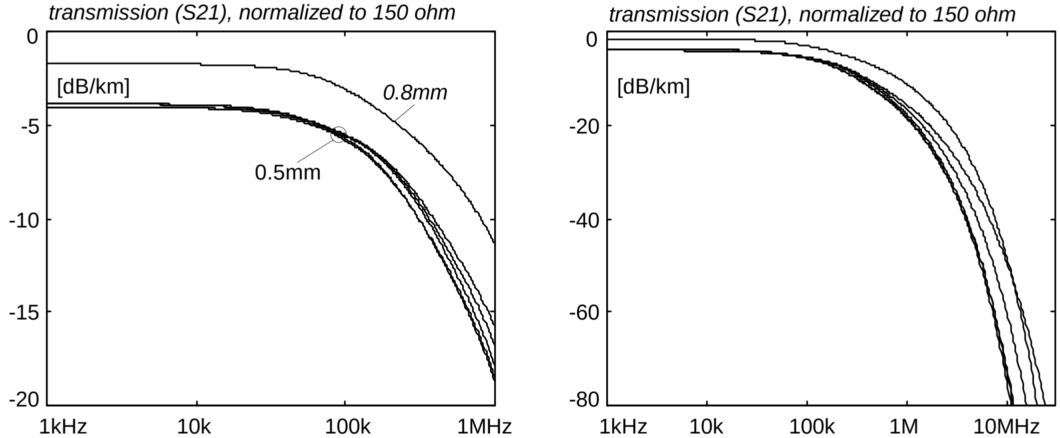

Figure 9 *Simulated transmission over 1 kilometer of Dutch cables. Both plots show identical curves but on a different frequency scale. In de ADSL frequency band, the insertion loss is dominantly related to the diameter of the wires, but in the VDSL frequency band the dielectric losses become more relevant. The average insertion loss at 10MHz is 60dB/km at a spread of 15dB/km.*

3.3. Wire-pair averaging by cascading sections

To average the spread in cable characteristics per unit length, the length of the cable sample was taken as long as possible. In practice this length is limited by the dynamic range of the measurement setup or by the length of available samples. Therefore the measured two-port s-parameters of the individual wire pairs in the cable were *mathematically* cascaded to tens of kilometers.

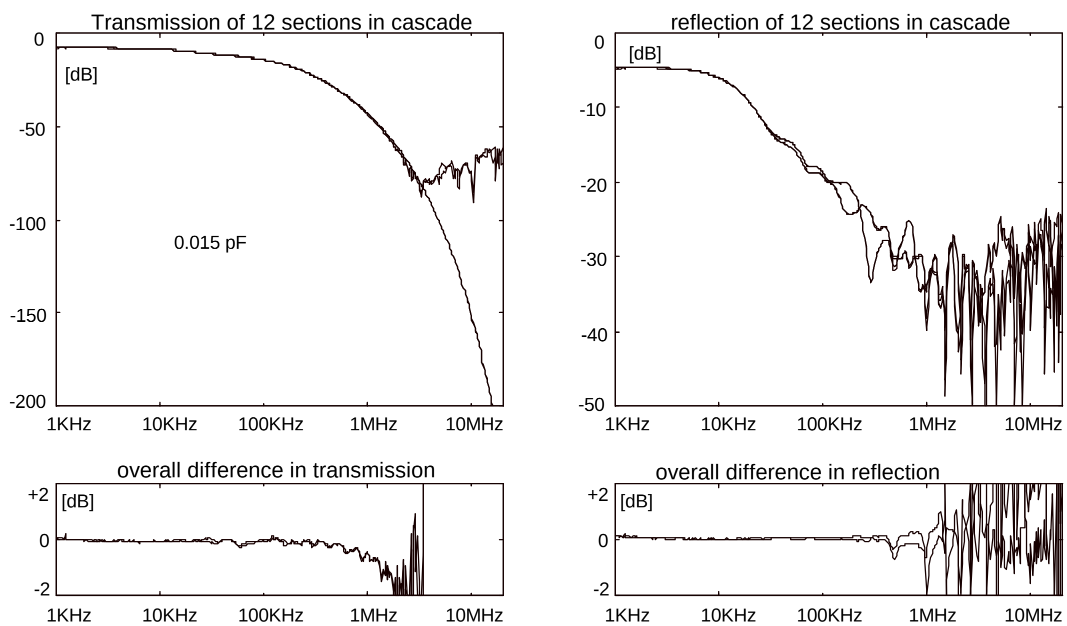

Figure 10. *Comparison between a mathematical cascade **of** 12×200m cable sections and an actual cascade of 2400m. Figure 11 shows the spread in transfer between the individual sections.*

Figure 10 is indicative on the robustness of this approach. Twelve different sections have been measured individually (12×200m), as well as in cascade (2400m). The figure shows the resulting curves of the s-parameters of the actual cascade, and the mathematical cascade. The relative difference between both curves is shown as well in figure 10, and becomes significant above 1MHz. This is caused by parasitic crosstalk errors in the measurement setup, that made the actual cascade less accurate than the mathematical cascade. Figure 11 shows the spread in transfer between the individual sections.

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 match the average cable within 0.05dB/m, then *the error would have exploded to 50dB/km*!
The difference between individual models fitted to individual sections is significantly smaller than the spread in insertion loss. This is also illustrated in figure 11. As a result, there is no need for further improvement on models.

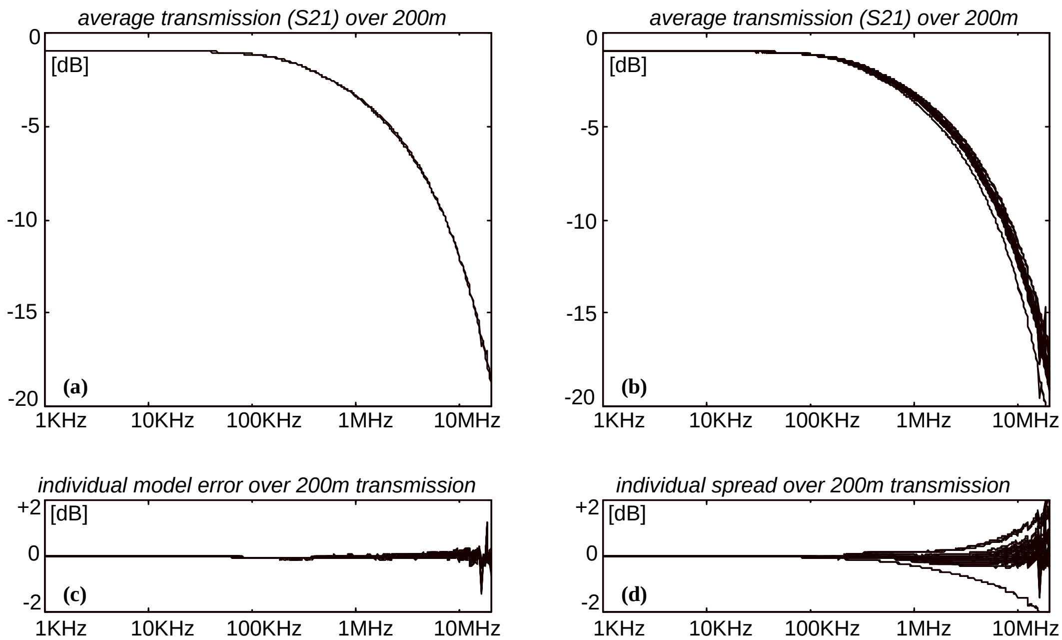

Figure 11 Spread in transfer between(a) measurement and dedicated model of sections, and (b) between measurement and average model of sections. This illustrates that there is no need to improve the model of the KPN_KK cable, because the spread in transfer exceeds modeling errors.

Figure 12 illustrates the fitting accuracy between dedicated model and measurements, on transmission (s_{21}), reflection (s_{11}), characteristic impedance (Z_0) and characteristic loss (α). All 24 sections of the KPN_KK cable have been cascaded (mathematically) for these plots. Figure 13 shows similar results on the primary parameters. It illustrates that an excellent fit on two-port parameters does not necessarily result in an excellent fit in series resistance (R_s) nor shunt conductance (G_p).

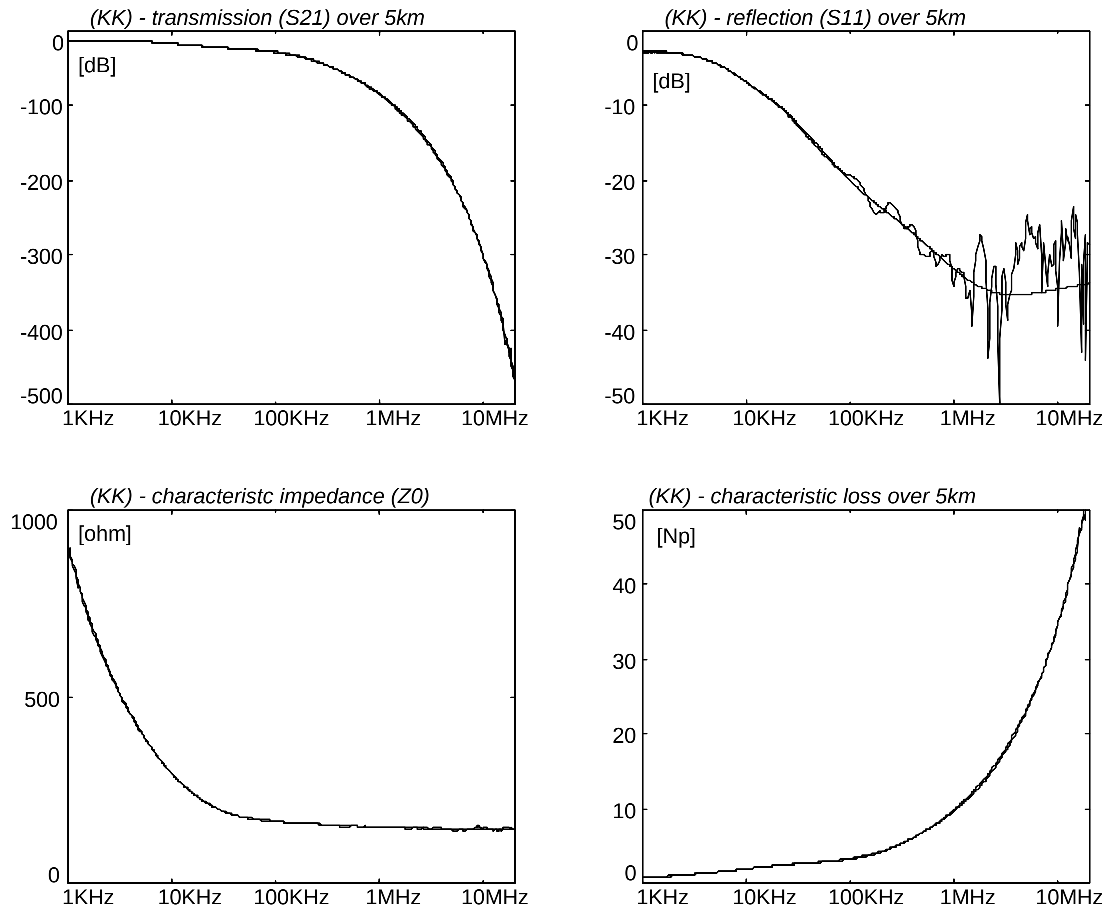

***Fig 12**. Fitting accuracy between measurement and modelling.*

3.4. Fitting strategy

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 $M \equiv 1$.

4. Conclusions

- Models extracted from measurements on cable longer than 1km are feasible,. This approach minimizes errors due to spread in cable characteristics per unit length.
- Mathematical cascading has proven effective to enhance the dynamic range of transmission measurements, and enables modeling on cables that are longer than tens of kilometers.
- The use of the "KPN#1" model, in combination with the minimizing on the error in S_{21} and Z_0, results in an overall modelling accuracy that is better than the spread in cable characteristics per unit length.

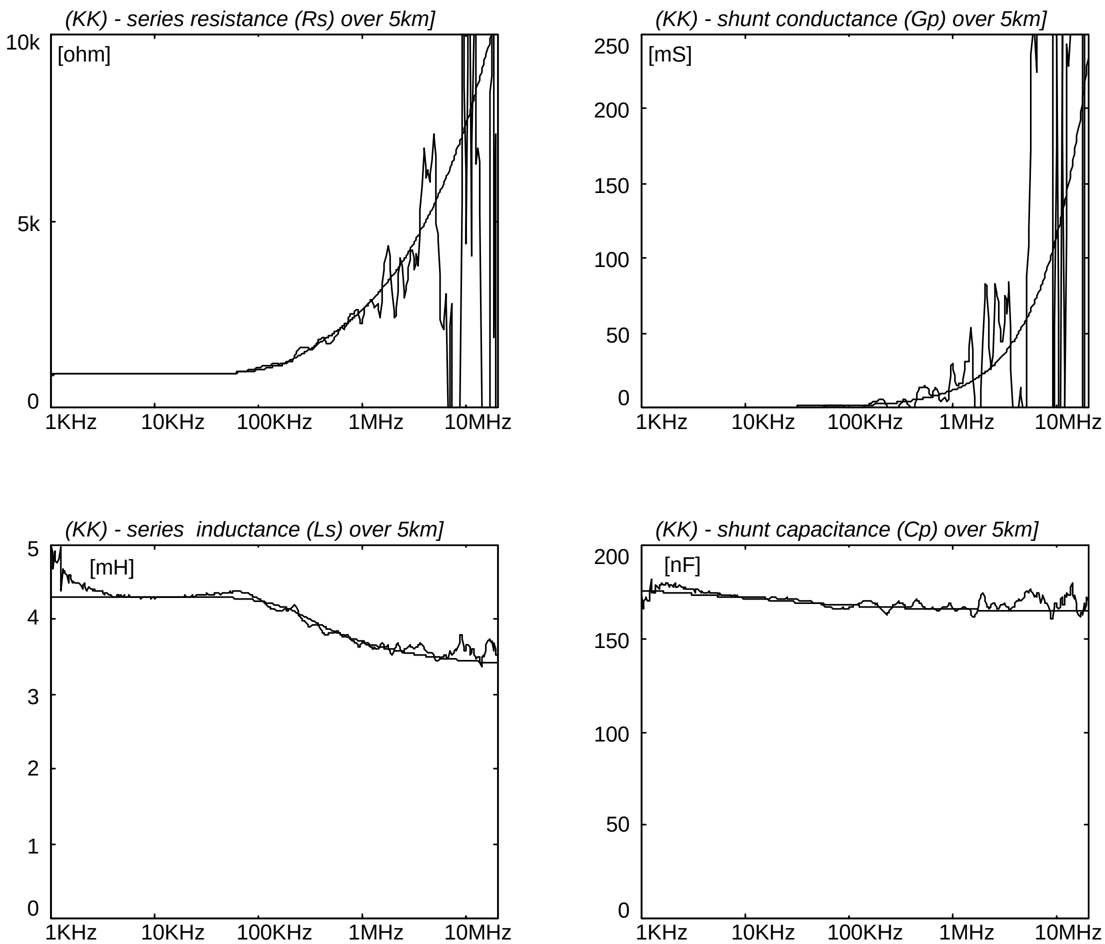

***Fig13**. Fitting accuracy between measurement and modelling on primairy cable parameters.*

5. References

[1] John W. Cook: ' **Parametric modelling of twisted pair cables for VDSL ',** ETSI contribution TD22, Vienna, Austria, march 1996.

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[3] Rob van den Brink: **'A round robin test on cable measurements',** ETSI-TM6 contribution TD16, [971t16r0], Tel Aviv, Israel, 10-14 march 1997.

[4] Rob van den Brink: **'Simulation models on metallic access cables',** ETSI-TM6 permanent document ETSI/STC TM6(97)02, [970p02r0], Tel Aviv, Israel, 10-14 march 1997.