ITU - Telecommunication Standardization Sector Temporary Document 11BM-021

STUDY GROUP 15 Original: English

Conference Call – 18 April 2011

Question: 4/15

SOURCE: TNO

TITLE: G.fast: Wideband transfer and crosstalk measurements on twisted pair cables

ABSTRACT

This contribution is a covering letter for the attached research report, that contains wideband measurement results for various twisted pair cables. This report is provided to the ITU-T to assist in the development of G.fast solutions. It addresses the issue proposed in [2] for developing wideband reference models for loop segments up to hundreds of MHz.

1. Introduction

A recent Broadband Forum presentation [1] in the open SPAC session motivated in detail the techno-economic need for a new copper technology to enable 4GBB service packages (consuming hundreds of Mb/s) via the last copper drop of a hybrid Fiber-to-the-Home scenario. The technical feasibility of the proposed concept was also motivated in that presentation [1] by means of wideband measurements on twisted pair cables.
At the end of that BBF meeting, a liaison was sent to ITU and resulted in the creation of a new work item, called G.fast.

G.fast transceivers are envisaged to work over twisted pair cabling and to utilize frequencies up to hundreds of Megahertz. To develop transceivers for this, detailed knowledge is needed about the transmission properties of the last copper drop of such loops at these high frequencies. These properties include insertion loss, impedance, crosstalk coupling, etc. Such knowledge is commonly available for frequencies up to 30 MHz but this does not hold for frequencies up to hundreds of MHz.

Contribution [2] proposed to develop reference models for various loop segments, in order to predict the characteristics of loops via a mathematical cascade of individual loop segments. These loop segment include cable sections of all kinds of multi-par cables, splices and manipulation boxed.

The present contribution unveils the results of an extensive cable measurement campaign by TNO and were used within [1]. This research was conducted in the Celtic 4GBB project [3], and the document was only the TNO part of a multi-document 4GBB deliverable. The attached research report describes wideband measurements results for three types of twisted pair cables:

- A high quality cable with 4 twisted wire pairs (category 5, for Gigabit Ethernet networks)
- A medium quality telephony cable with 30 twisted quads (60 wire pairs), as typically used in the Netherlands.
- A low quality telephony cable with 2 wire pairs (untwisted), found in a consumer shop.

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These measurements are to support further development of wideband reference models for loop segments, as first input for the issue proposed in [2]. It is the intention of the authors of the report to follow up on these measurements by developing parametric models for the investigated cables and by providing similar measurements on other cables as well.

2. Reference

[1] Rob F.M. van den Brink, "*Enabling 4GBB via Hybrid-FttH*", Broadband Forum presentation bbf2010.1395.00 , San Francisco, dec 2010.

[2] TNO (Brink, Heuvel), *"The need for wideband reference models of loop segments within twisted pair cable topologies"*, ITU contribution 11BM-020, April 18, 2011.

[3] 4GBB Consortium, cooperating as a project under the EUREKA CELTIC cluster. See *www.4gbb.eu* for further details.

3. Summary

This contribution is a covering letter for the attached research report, that contains wideband measurement results for various twisted pair cables. These measurements are to support further development of wideband reference models for loop segments, as input for the issue proposed in [2].

WIDEBAND TRANSFER MEASUREMENTS ON TWISTED PAIR CABLES, PART 2 – TNO RESULTS

DOCUMENT IDENTIFICATION

Doc number:	WP3_0121_V00_CableChar_TNO
Title:	**Deliverable 3.3**: Wideband transfer measurements on twisted pair cables, part 2 – TNO Results
Author(s):	Rob van den Brink, Jeroen Boschma, Mariya Popova (all TNO)
Abstract:	The maximum data rate that can be transported via a given access network requires a good understanding of how signals are transmitted through its cabling. Characterizing cables is therefore an essential step for creating computer models on cable characteristics to enable performance studies by means of simulations. This characterization does not only require all kinds of transfer functions like transmission, reflection and crosstalk but also derived properties like characteristic impedance, primary cable parameters etc. This document is the second part of a multi-part deliverable, and describes in detail the characterization of various Dutch cables by TNO. This includes a high quality cable with 4 twisted wire pairs (category 5, for Gigabit Ethernet networks), a medium quality telephony cable with 30 twisted quads (60 wire pairs) and a low quality telephony cable with 2 wire pairs (untwisted), found in a consumer shop. More cables will be incorporated in a future revision of this document.

DOCUMENT HISTORY

	Date	Author	org	modification
V01	03-02-2011	Rob van den Brink	TNO	Creation from existing working documents and new analysis results
V02				
V03				

TABLE OF CONTENT

MANAGEMENT SUMMARY

Problem to be solved: The maximum data rate that can be transported through a given access network is highly depended on the characteristics of the used (twisted pair) cabling, being designed for transporting analog telephony signals. Insertion loss and crosstalk coupling in these cables are the key factors of these limitations, and they have been studies in the past for ADSL and VDSL applications (typically up to 30MHz). But the transportation of a 4GBB service package requires modem signals that are much higher in frequency and very little is known on these cables beyond 30MHz. This troubles the prediction of the maximum attainable data rate that can be delivered via such access networks.

Aims: The aim of wideband transfer measurements on twisted pair cables is to get a much better understanding of the transmission of signals in these cable at higher frequencies. It should provide the missing information needed for making computer models for these kinds of cables, so that the maximum attainable data rate can be predicted by means of realistic simulations. The present document is concentrated on twisted pair cabling being used in the Netherlands, especially those that are deployed in the access network of KPN, that are installed in buildings and end-user houses.

Results: This reports summarizes relevant properties from a variety of twisted pair cables. Properties like transfer functions, characteristic impedance and primary cable parameters are shown in this document up to a maximum usable frequency or up to 500MHz. But there are many more properties that TNO can now easily extract from all kinds of cable measurements (organized in a cable database) by means of an advanced dedicated software tool. The cables being analyzed so far are:

- A high quality cable with 4 twisted wire pairs (category 5), typically used for interconnecting Gigabit Ethernet networks. It appeared to be capable of easily transporting hundreds of MHz of 200m or more.
- A medium quality cable with 30 twisted quads (60 wire pairs), typically used within buildings for interconnecting analog telephony. It appeared to be capable of transporting signals up to 50-100MHz if it is 200m long. This frequency range should enable several hundreds of Mb/s.
- A low quality cable with 2 wire pairs (untwisted), found in a consumer shop and sold as “telephony cable”. It appeared to be capable of transporting signals up to 50MHz id it is “only” 50m long.

This is just the status at the time of writing this document. The characterizations of other cables will be added by TNO in near future, especially those that are being deployed in the Dutch access network.

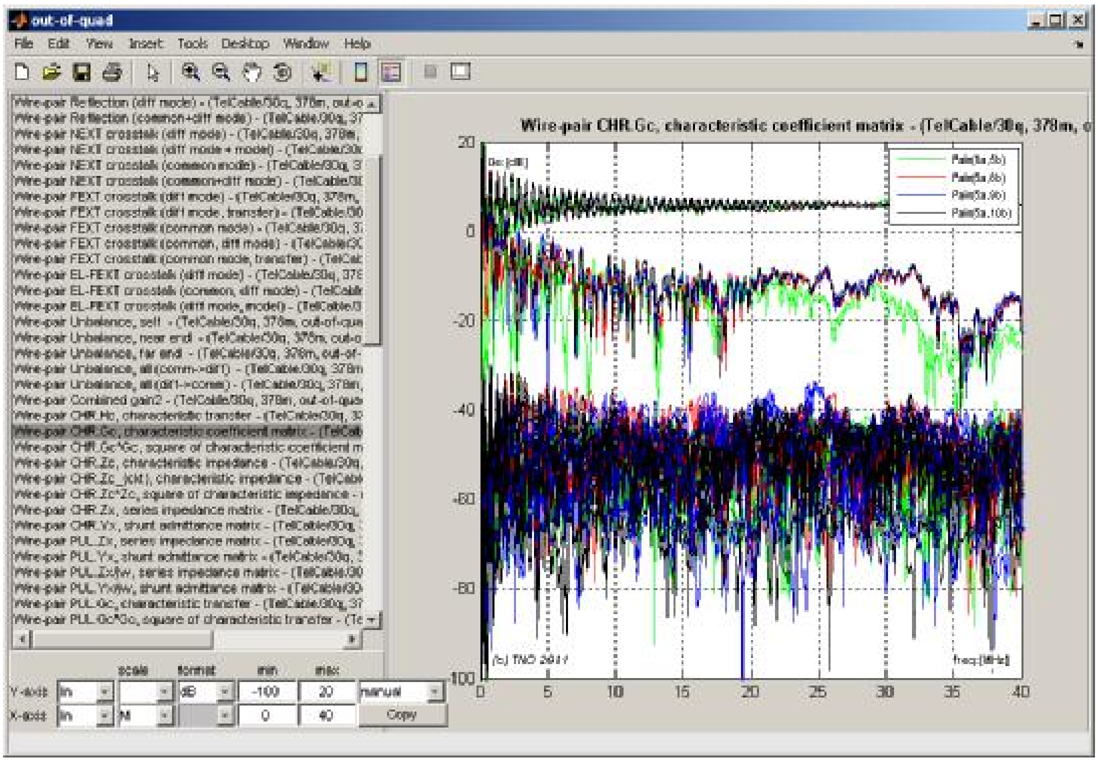
Follow up: The next step is to create computer models from these characterizations to enable performance studies by means of simulations and to do more of these characterizations. This does not only include more cables but also all kinds of cable irregularities like spices, manipulation points, etc.

1 INTRODUCTION

Characterizing cable properties is an essential step in the development of realistic models performance studies. Such studies are needed to analyze what bitrates are achievable for 4GBB in a given access network.

1.1 What has been characterized?

This document describes the properties of a diversity of twisted pair cables, ranging from very high to very low quality, and with shielding or not. They are analyzed in great detail by developing dedicated software tool for extracting all kinds of properties from the multiport measurements. Especially the algorithms for extraction of (multiport) characteristic impedance and (multiport) primary cable parameters are quite advanced. The most relevant properties are shown in this document, but the software tool give access to a plurality of properties from measurement stored in a database.



Currently, the following cables have been characterized:

- A high quality cable with 4 twisted wire pairs (category 5), typically used for interconnecting Gigabit Ethernet networks.
- A medium quality cable with 30 twisted quads (60 wire pairs), typically used within buildings for interconnecting analog telephony.
- A low quality cable with 2 wire pairs (untwisted), found in a consumer shop and sold as "telephony cable".

This is just the status at the time of writing this document. The characterizations of other cables will be added in near future, especially those that are being deployed in the Dutch access network.

We did not characterize properties for predicting ingress and egress, since it would require a very different measurement setup as well. Such information is essential for predicting if transmitted signals levels will interfere with broadcast radio stations, or if RFI (radio frequency interference) from radio stations will be a problem of major concern.

1.2 Cable properties of primary interest

All cables in this document are characterized as multi ports, having 8 ports. A port can refer to a single wire end ("Direct mode") or to the end of a wire pair ("Mixed mode", for differential and/or common mode transfer). All cables in this document are measured in "Direct Mode" and when needed this representation is converted in a mathematical manner to "Mixed mode". If the cable has more than 8 wire ends, the remaining wires are not terminated with 100 ohm, unless explicitly specified as terminated.

A full description of what properties have been extracted, how they are extracted and how the are defined is beyond the scope of this document. But from all extracted properties this document shows the following properties:

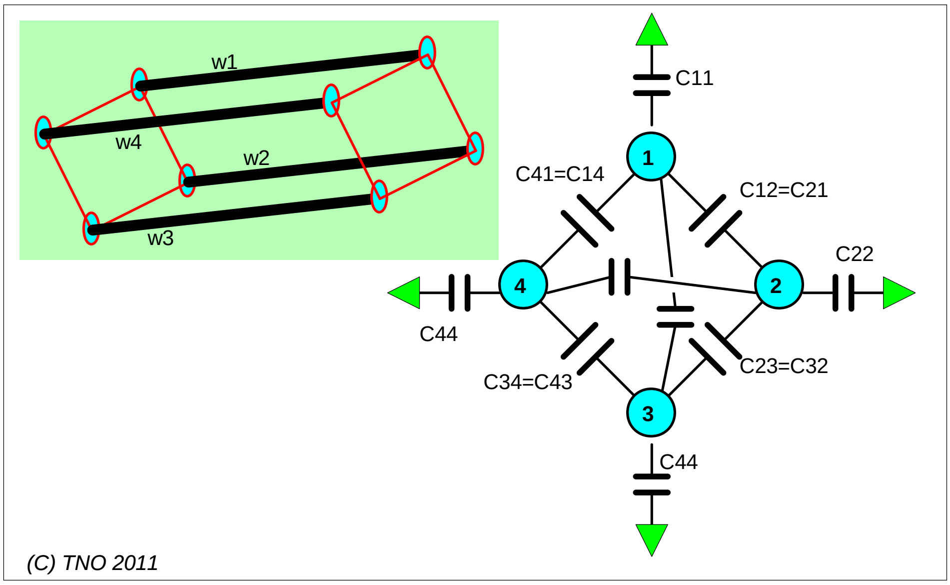
- ***Scatter parameters*** normalized to reference impedance R_N = 100 ohm. Parameter S_{kr} refers to a transfer function when signal is injected into port r and detected at port k. Normalized to a (real) reference impedance means in this context that source and load impedance are equal to that (real) reference impedance.
  - Transmission: if ports are at both ends of a wire or a wire pair.
  - Reflection: if both ports are the same (k=r).
  - NEXT: if both ports are at the same side of the cable, unless it is reflection.
  - FEXT: if both ports are at apposite side of the cable, unless it is transmission.
  - Unbalance: if one of the ports is a wire pair and considered in differential mode and another port in common mode.

  The phase of the transmission is represented by means of a velocity factor (VF), representing the speed at which a traveling wave transmits through a cable, with respect to the speed of light. It is typically in the order of 0.7 depending on the dielectric properties of the insulation between the wires (geometry play hardly any role here).

- ***Characteristic impedance***. Parameter Z_c refers to a characteristic (multiport) impedance, representing the input impedance of a cable of infinite length. As a result, terminating the end of a homogeneous cable of finite length with impedance Z_c will also give the same impedance at its input. Since impedance Z_c represents a multiport, it is represented by means of matrix parameters (handy for calculations) and by means of equivalent circuit parameters (handy for physical interpretation)

- ***Primary cable parameters*** (RLCG). These parameters represents the series and shunt characteristics of the wires per unit length (typically per meter). They play a powerful role in multiport modeling of these twisted pair cables. The full details behind representing cables by their primary parameters and how they are extracted from measured s-parameters is beyond the scope of this document, but the following parameters are commonly used:
  - $L_{s,k}$ refers to the series inductance per unit length of wire k (or wire pair)
  - $K_{s,kr}$ refers to the mutual magnetic coupling per unit length between the wire k and wire r (or wire pairs). It has value $K_{s,kr}$=1 when k=r, and $|K_{s,kr}|<1$ when $k \neq r$. Note that $K_{s,kr} = K_{s,rk}$.
  - $C_{p,kr}$ refers to the capacitance per unit length between the wires (or wire pairs) when $k \neq r$, or between wire (wire-pair) and shielding/ground when k=r. Note that $C_{p,kr} = C_{p,rk}$.
  - Restance (R) and conductance (G) are ignored for the time being, since their combination is responsible for the loss in the cable (which is often a smoothed curve), while the extracted values for R and G alone are nearly random in nature. This is subject for further study.

  The figure below illustrates this for a cable section with 4 wires (two wire pairs). Each wire has a series inductance, is electrically as well as magnetically coupled with another wire. So in this example has 4 values for L_s, and 16 values for K_s and another 16 for C_p, but several values are equal.
  Wires and their insulation have also a series resistance (R_s) and a shunt conductance (G_p), more or less similar with L_s and C_p.



1.3 Typical values / rule of thumbs found from the measurements

Although the studied cables are very different in nature, some of their properties have similar values. This observation is useful as rule of thumb and to do a quick check of measured parameters are plausible or not. So far the following has been observed:

- Insertion loss in the order of 10 dB @ 30 MHz @ 100m, or a bit higher.
- Velocity factor in the order of 0.68. This observation offers a powerful method for estimating the length of a cable.
- Differential mode characteristic impedance in the order of 100-135 ohm.
- Common mode characteristic impedance is about half the value for differential mode values.
- A pragmatic maximum usable frequency of a cable with given length can by found at the first intersection of the transmission curve and the FEXT curve If the far end crosstalk beyond a certain frequency gets so worse that signal and crosstalk are in the same order of magnitude, then such cable isn't really useful for such high frequencies.

2 HIGH QUALITY, CAT 5 CABLING

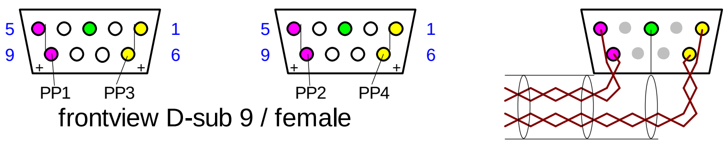
The first cabling being characterized is a cable with 4 twisted wire pairs and a common shielding. It is a cable with high quality twists (category 5 quality or better), so that crosstalk between other wire pairs is kept to a minimum. This cabling is typically used for interconnecting 1 Gb/s Ethernet equipment with 100Ω source and load impedances.

2.1 Description

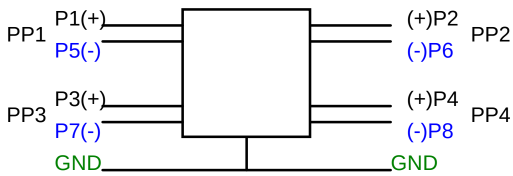
A cable of about 300m was cut into three individual pieces of different lengths, to create different sections named as “232m”, “61m” and “10m”.

- The length of the **“61m” section** was physically measured at **61.15m** with high accuracy.
- The length of the **“232m” section** was estimated afterwards at **235m** by comparing the measured velocity factors of “232m” and “61m” . If this length would have been estimated from DC resistance measurements, a length of 229m would have been estimated. However, if we assume that the manufacturer offered a drum of 300m, of which 10+61m has been removed, then the remaining length could have been estimated at 229m. So these are all slightly different estimates, but we assumed that the approach with length scaling via velocity factors is the most reliable one.
- The length of the **“10m” section** was estimated afterwards at **10.21m** by comparing the measured velocity of “232m” and “61m”. (Recent measurements of the physical length showed that the actual length was 10.0m, or 2% shorter, but this difference has not been incorporated in the measurements below).

Two of the 4 wires in each section was subsequently interconnected with the outer PINs of a D9-connector, and they were characterized. The shielding of the cable was connect to the center PIN of that connector to enable a common return path during the direct measurements of the devices.



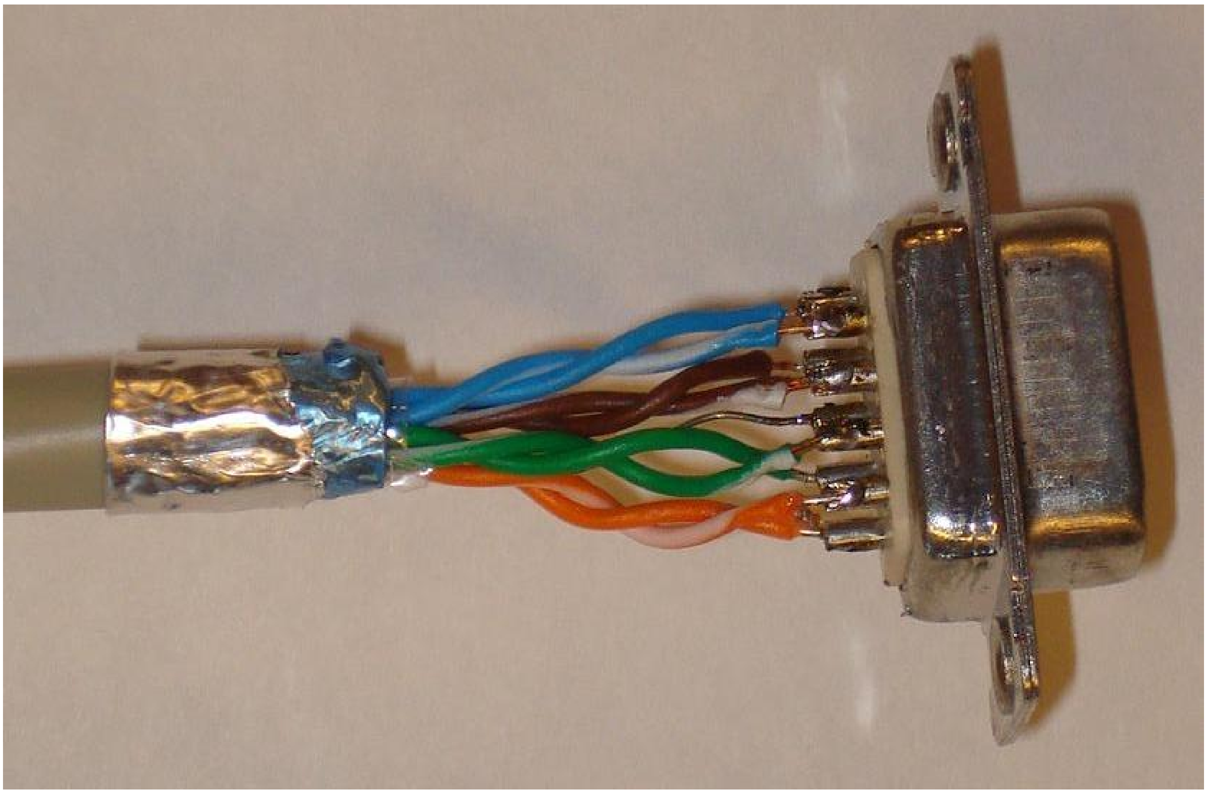
frontview D-sub 9 / female



Section “232m” (=235m)	Wire resistance	remarks
PP1/PP2	19.8 + 19.9	0.169 ohm/meter
PP3/PP4	19.5 + 19.5	0.166 ohm/meter
DC-resistance of return (shielding)	??? Ohm	
Section “61m” (61.15m)	**Wire resistance**	**remaks**
PP1/PP2	5.15 + 5.15 Ohm	0.168 ohm/meter
PP3/PP4	5.12 + 5.12 Ohm	0.167 ohm/meter
DC-resistance of return (shielding)	1.83 Ohm	

Since this cabling is shielded, the “232m” section could remain on its drum without introducing parasitic crosstalk coupling between the windings on that drum. And the “61m” section was winded on another drum (and was also used for the Round Robin test). Several of the involved constructions are shown below:

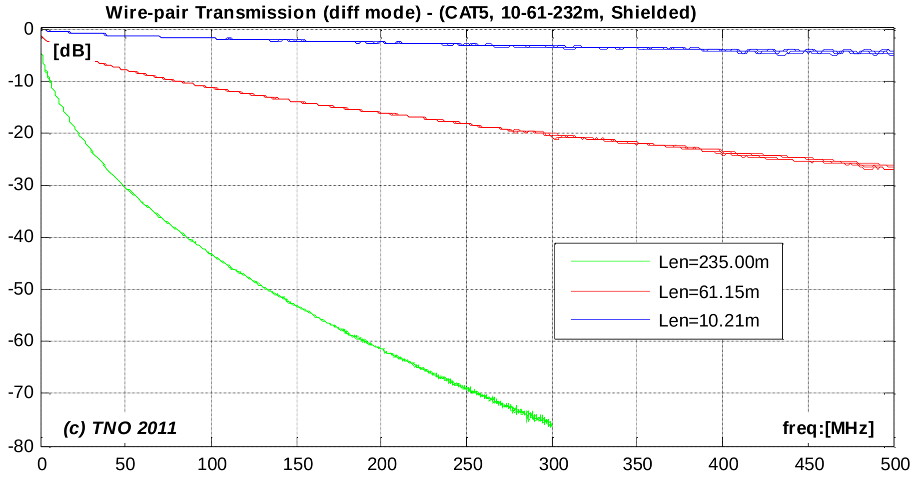
"232m" (=235.00m)	
"61m" (=61.15 m)	
"10m" (=10.21m") 10.0m	NO PHOTO AVAILABLE

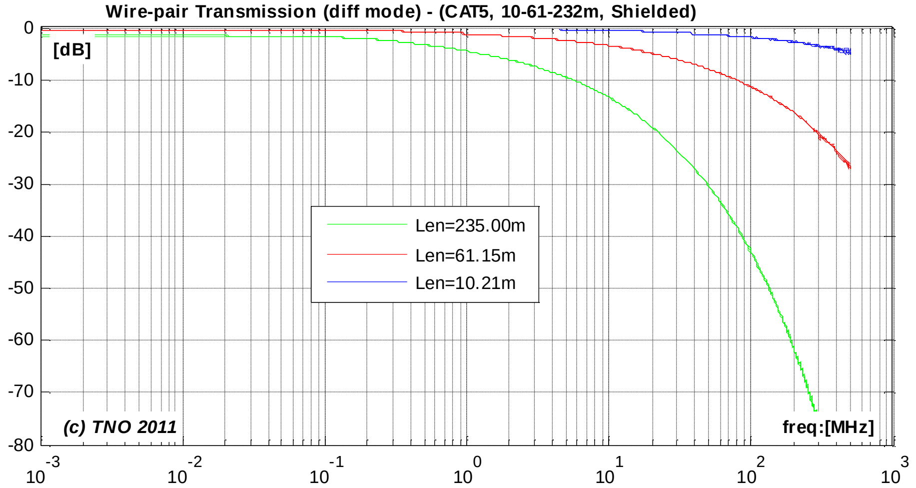


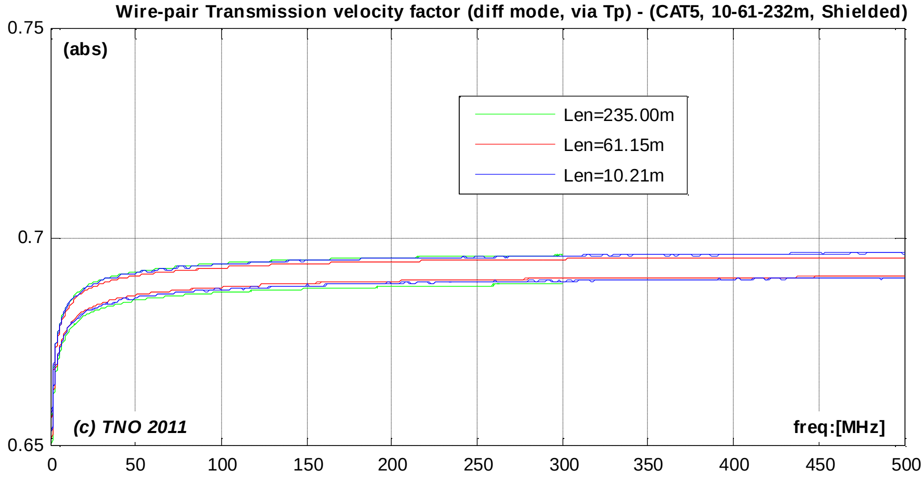
2.2 Transmission

2.2.1 Differential mode

Differential mode transmission via this cable shows smooth curves up to 500MHz, and this demonstrates the high quality of this type of cabling. It learns that the typical insertion loss is It learns that the typical insertion loss is **9.91dB** @ 30MHz @ 100m on average. The observed velocity factor is in the order of **0.69**, which is considered as typical for these types of cabling. The spread in velocity factor between the wire pairs is in the order of 0.7%, which can be explained by assuming that the different wire pairs are not perfectly equal in length.

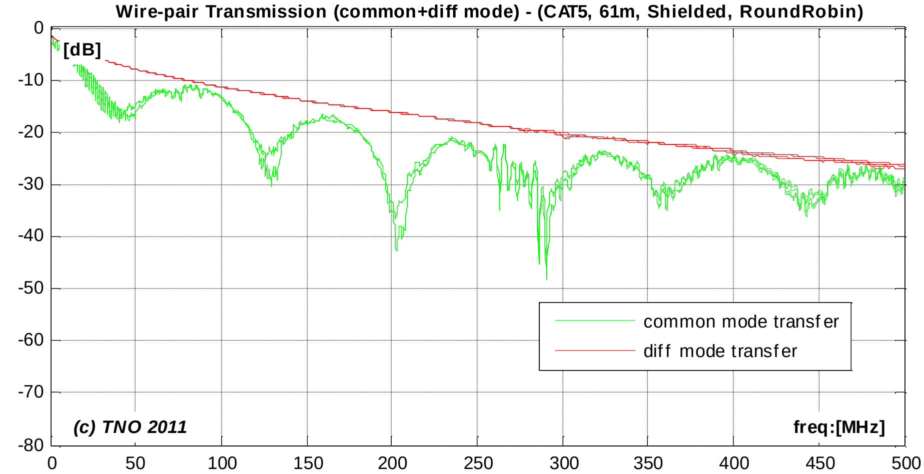


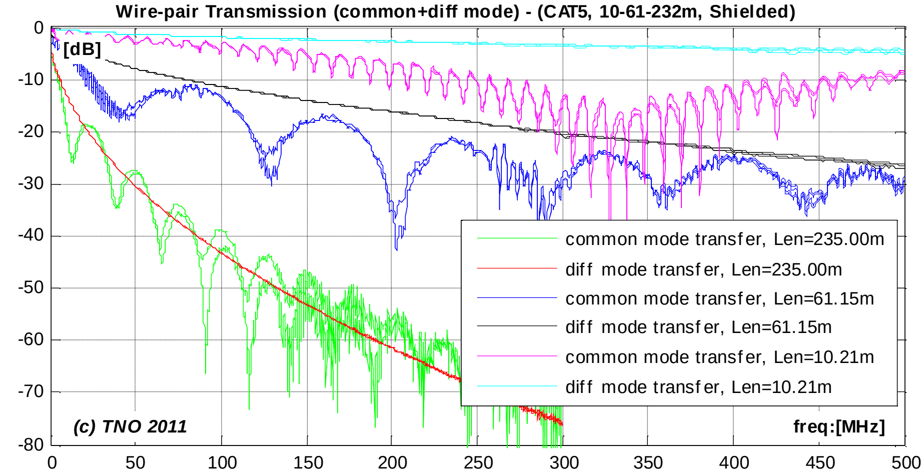




2.2.2 Common mode

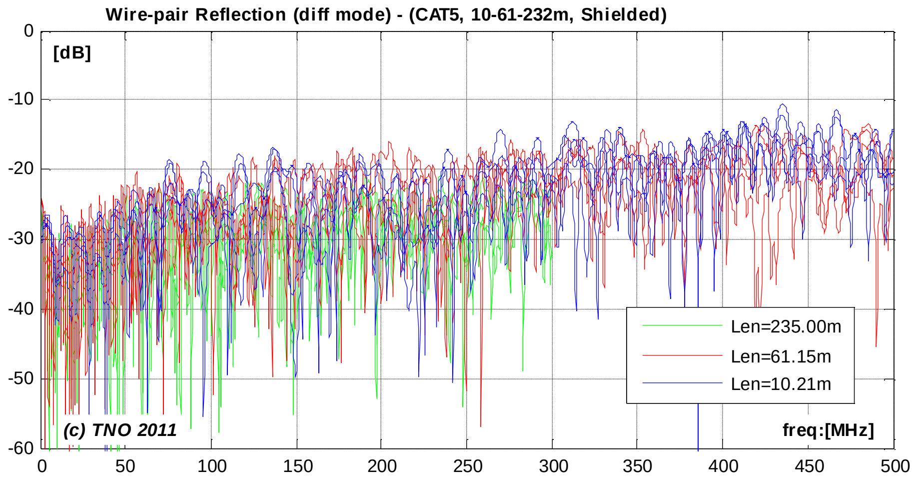
The common mode transmission is shown below and its curves are very rippling in nature. This may be obvious since the cable geometry is very irregular for common mode signals. Fortunately it is of no serious relevance for balanced transmissions and only shown here for the sake of completeness.

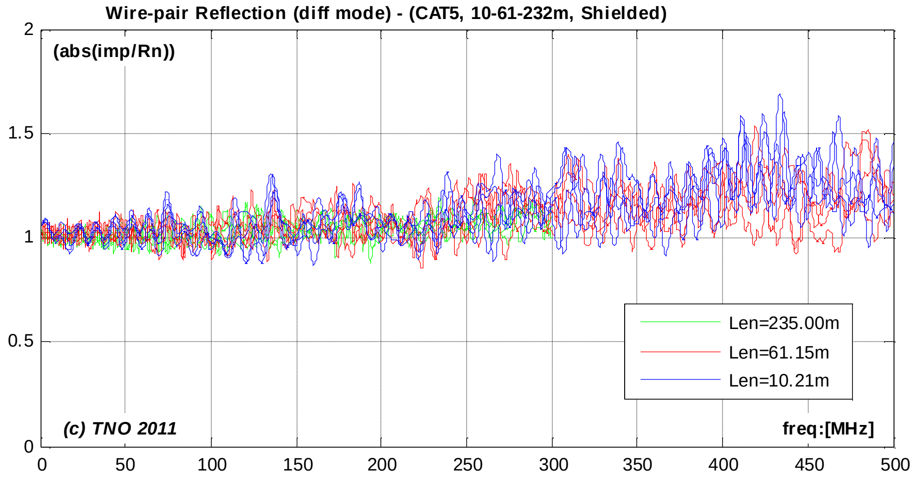




2.3 Reflection

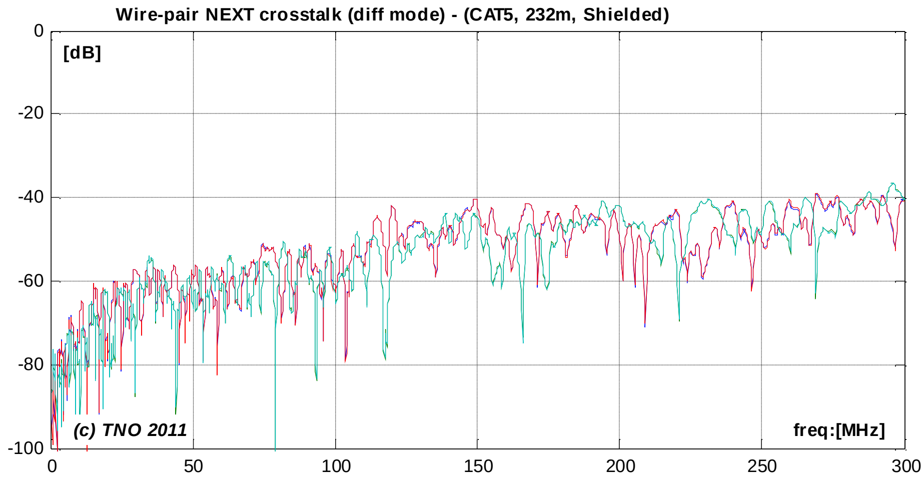
The differential mode reflection is related to the input impedance of the cable and the reference impedance (R_N) used for representing the measured s-parameters. Both are shown below. The input impedance is about 100Ω at low frequencies, and increases a bit towards higher frequencies. It is rather independent from the loop length.

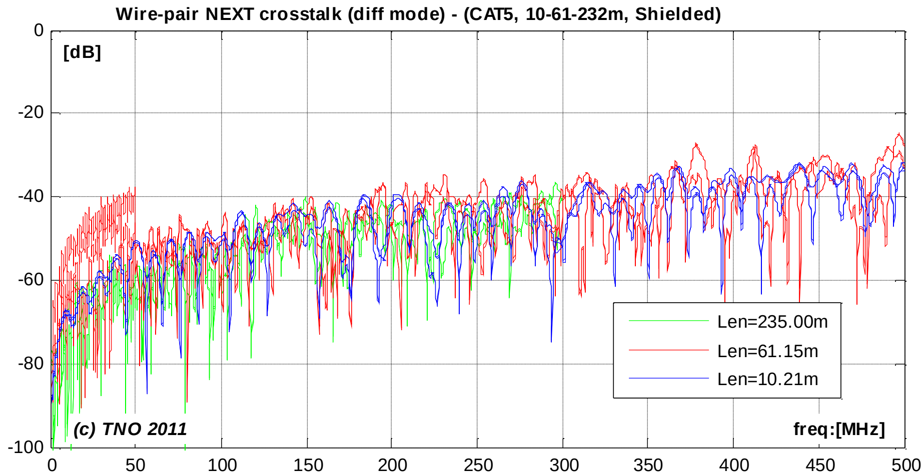




2.4 Near end crosstalk coupling (NEXT)

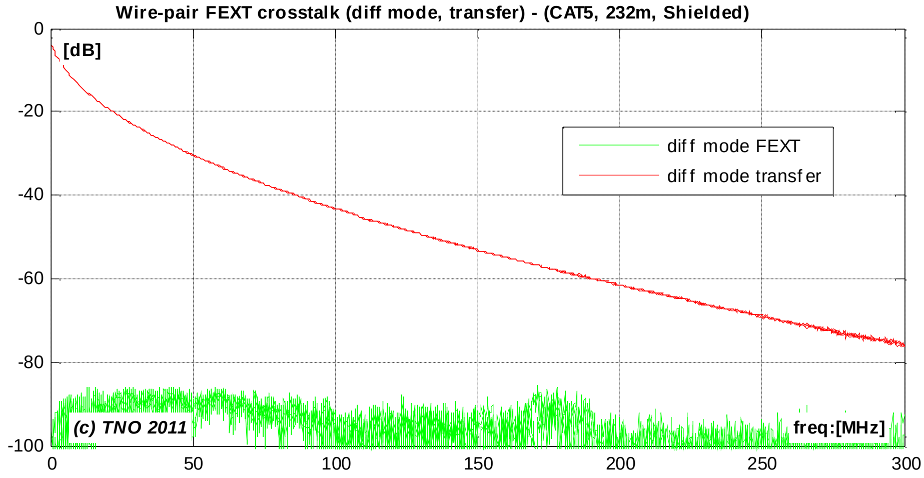
The differential mode NEXT is dependent from the length of the loop, but all are in the same order of magnitude. One of the measurements (on the “61m” section) shows an irregularity up to 50MHz which is probably caused by a small error during the 1-50MHz sweep in the measurements. It should be re-measured and is not of any concern.

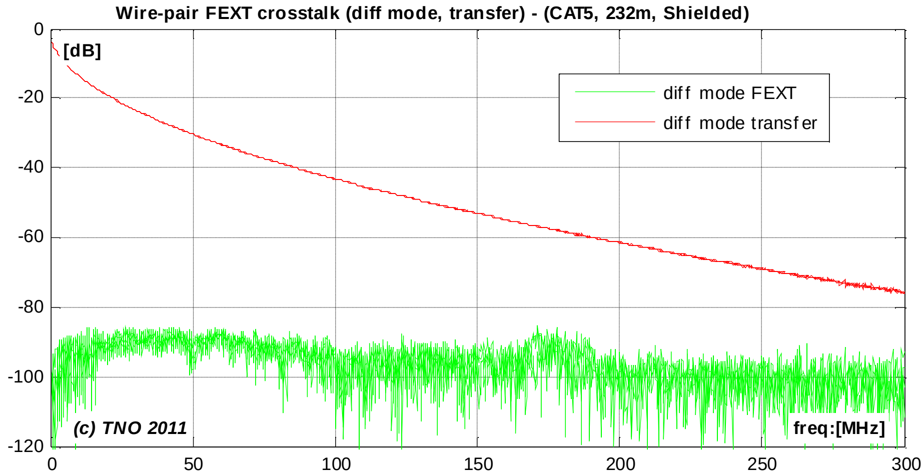


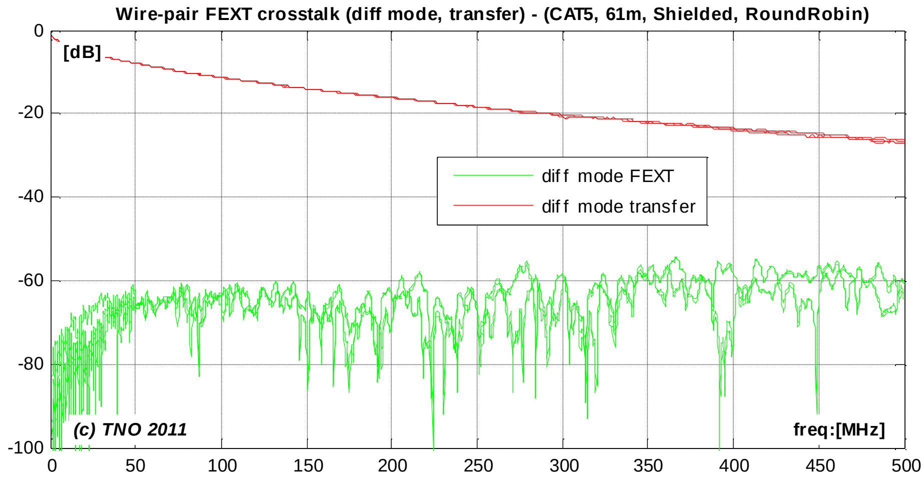


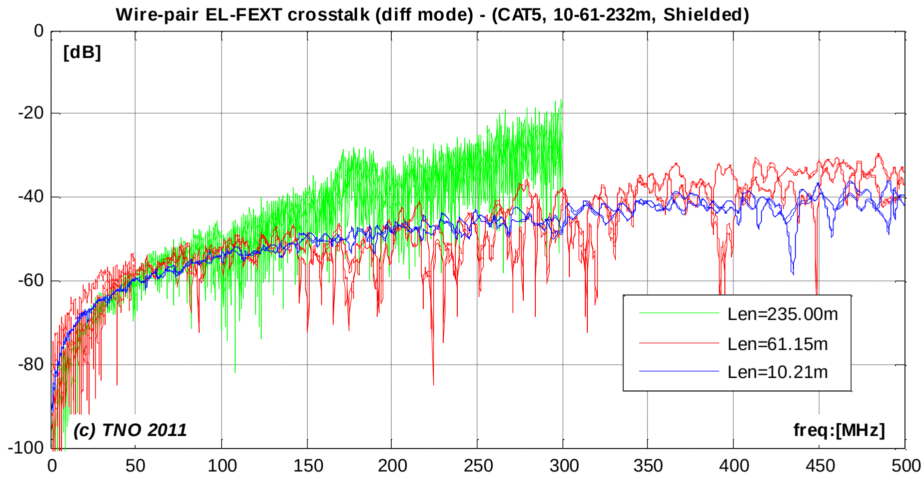
2.5 Far end crosstalk coupling (FEXT and EL-FEXT)

The differential mode FEXT is so close to the lowest values that are measurable with the present measurement setup that the curves are a bit deteriorated with noise. This again demonstrates the high quality of this cabling.
FEXT is s highly dependent from the loop length, and therefore we prefer to represent this crosstalk coupling is by means of the EL-FEXT (Equal Level FEXT), which is also shown below. The EL-FEXT for the "232m" section is probably lower in practice than measured here due to dynamic range limitations of the measurement setup.





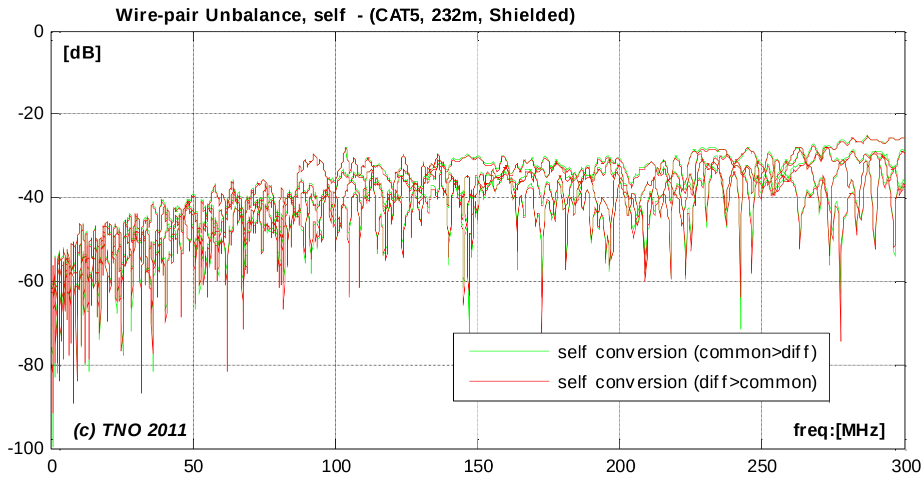


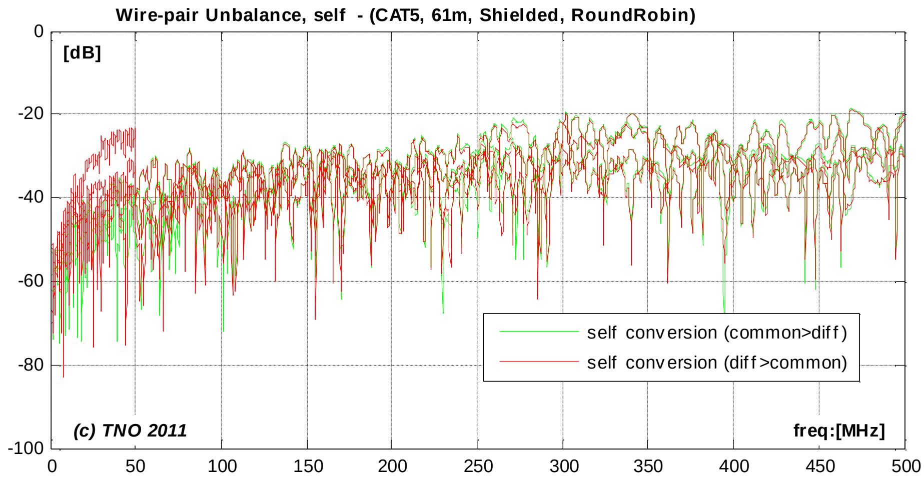


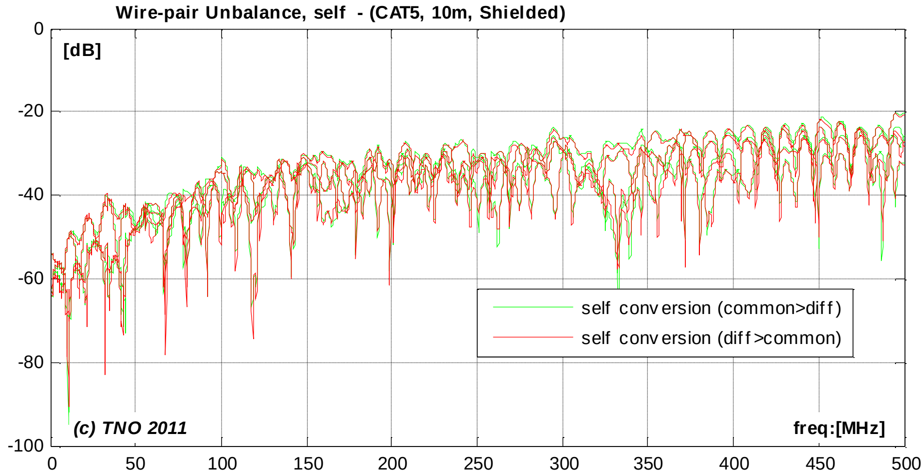
2.6 Unbalance

The unbalance of a cable expresses the conversion from common to differential mode if a common mode signal is injected, or the conversion from differential to common mode if a mode signal is injected. This is a reciprocal process, meaning that both conversion values are to be equal and the figures below illustrate how good this can be observed from the measurements.

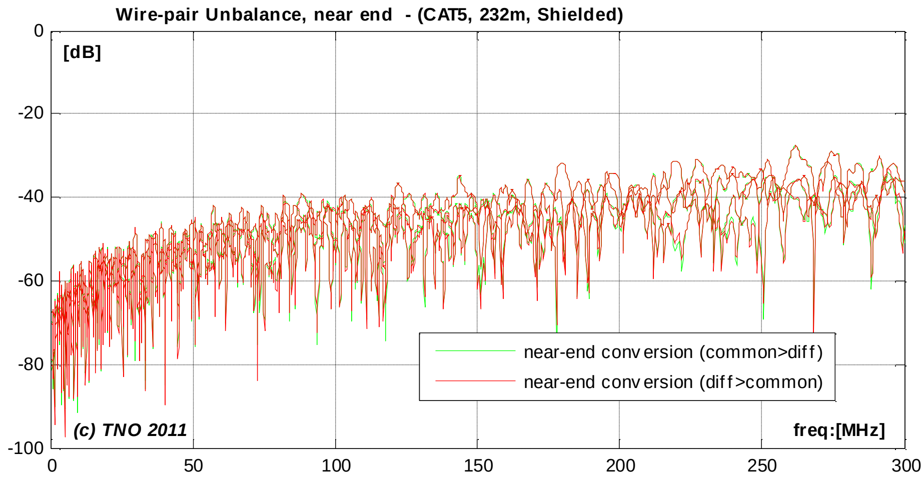
2.6.1 Self mode conversion

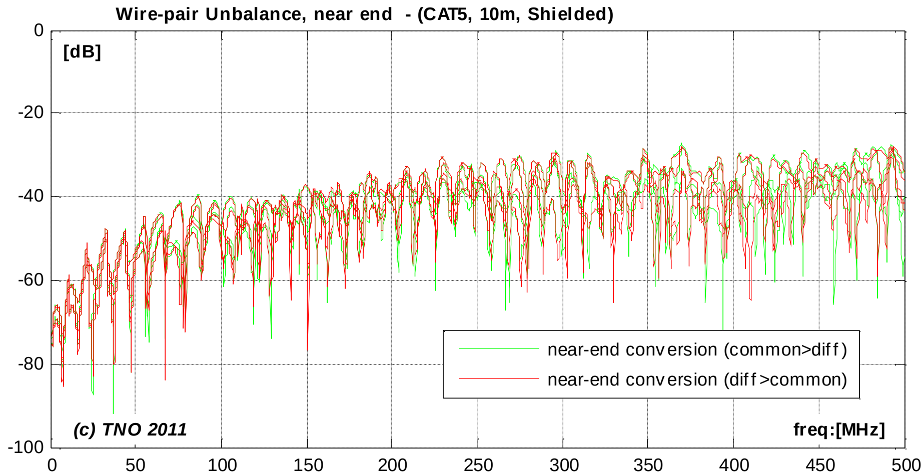


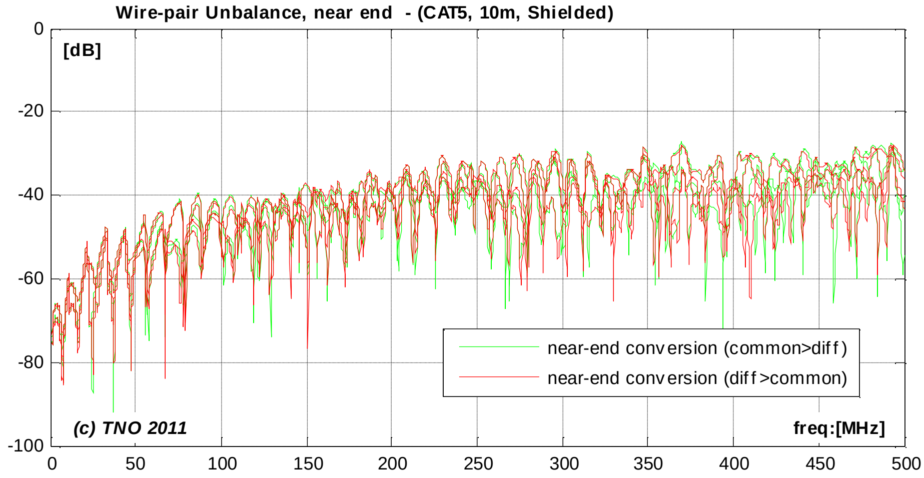




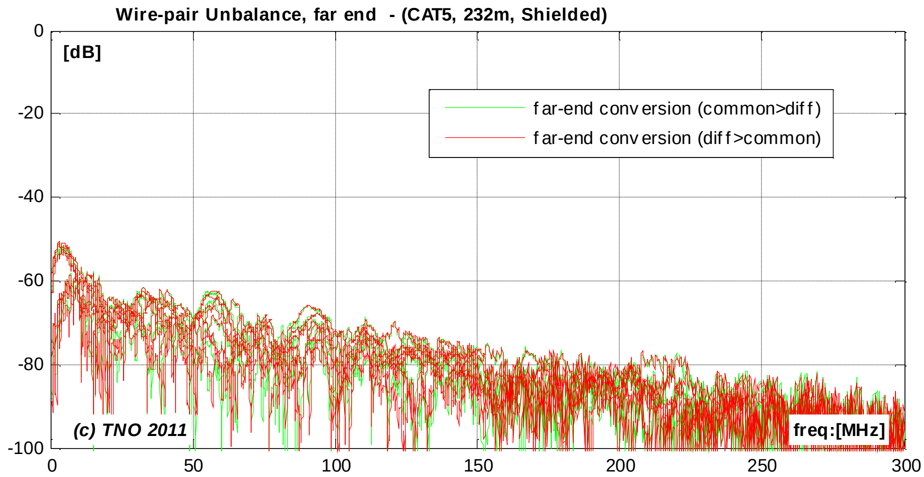
2.6.2 Near-end mode conversion

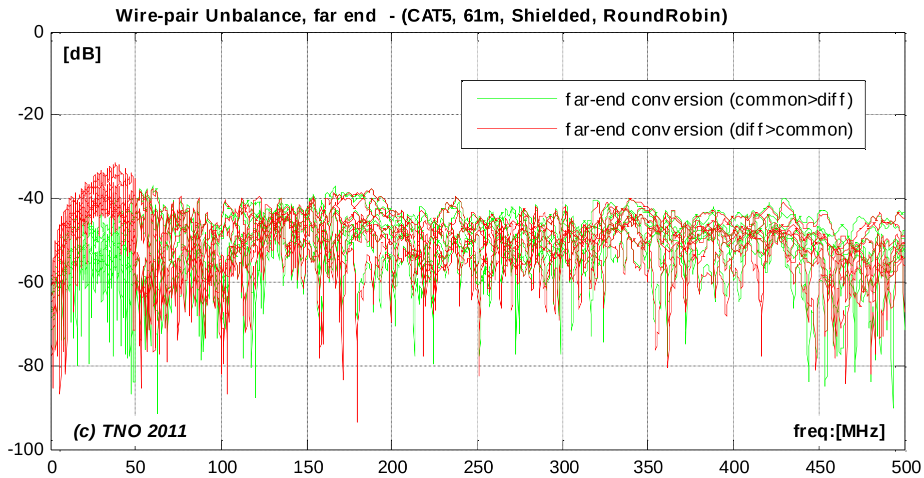


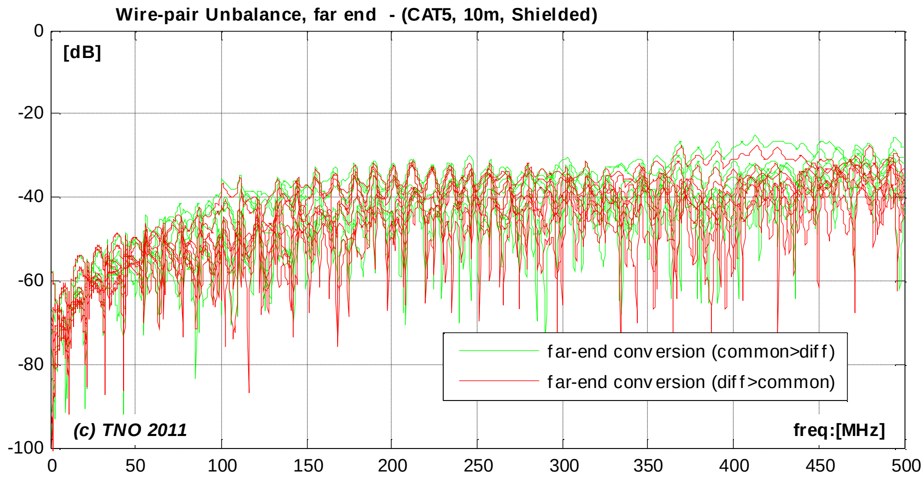




2.6.3 Far-end mode conversion







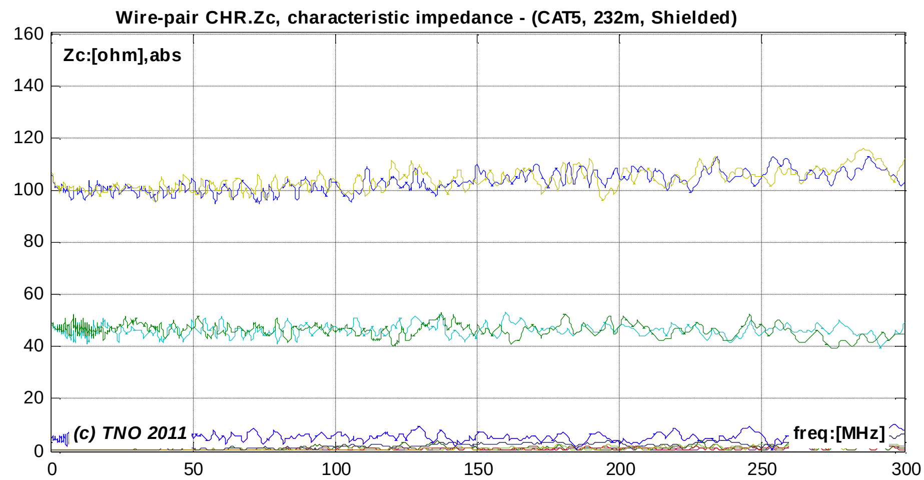
2.7 Characteristic impedance

The (multi port) characteristic impedance is indicative for the (multi port) input impedance of a very long loop. This multiport impedance can be represented by means of a matrix-representation (z-parameters are convenient for matrix calculations) and by means of an equivalent circuit representation (convenient for physical interpretation). Both are shown below.

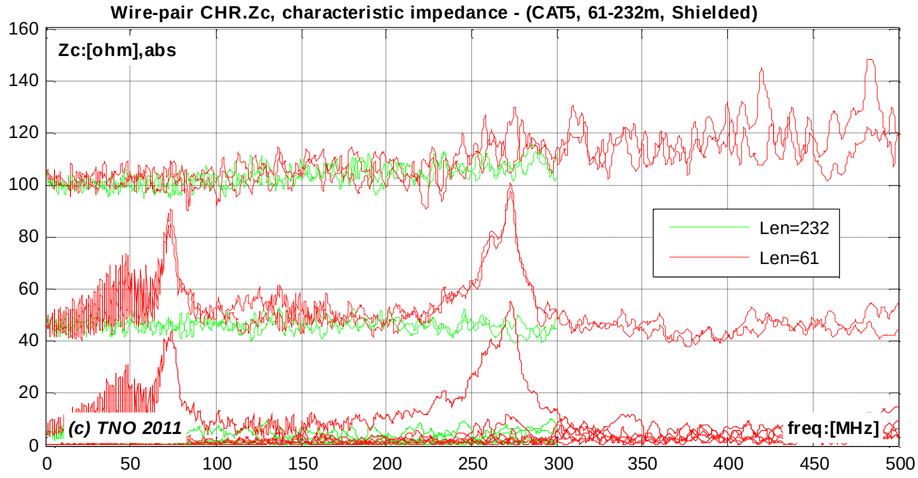
2.7.1 Matrix parameters (of wire pairs)

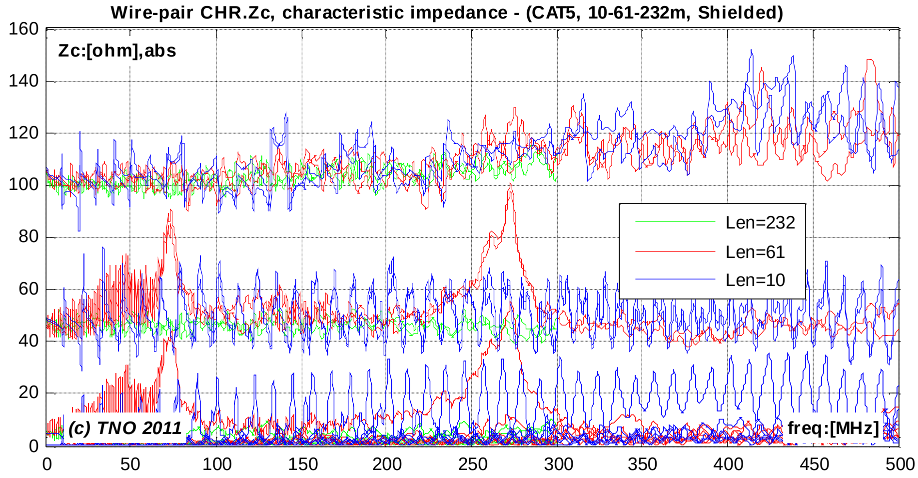
The figure below illustrates the z-parameter values of the (multi port) characteristic impedance for the "232m" section.

- The two upper curves, around 100ohm, represent the differential mode Zc.
- The two middle curves, around 47ohm, represent the common mode Zc
- All the others are the remaining coëficients of the (mixed mode) characteristic impedance matrix, and their meaning is more mathematical in nature.



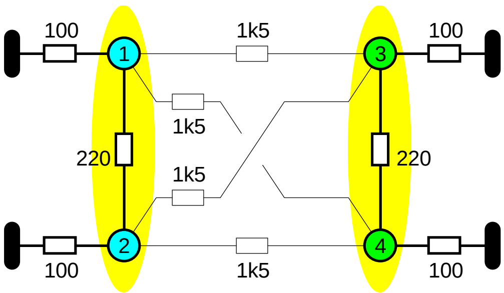
For shorter loops (64 or 10m) it appeared to become more difficult extracting the Z_c. The figures below show that the extracted values resonate around distinct frequencies, and that the spacing of resonation frequencies decreases with the loop length.
These values are to represent the input impedance of an infinite cascade of identical sections to emulate a cable of infinite length. This repetition of identical sections introduce regular reflections that resonate at frequencies related to the length of each section. These "resonations" are also visible (at a lesser extent) in the common mode and in the single wire input impedance when the other end of the loop is terminated with 100 ohm. Apparently this gets emphasized when Z_c is extracted by emulating an infinite cascade of sections. At the time of writing, this effect is not fully understood, and it is therefore also unknown if it can be prevented by modifying the extraction algorithms.

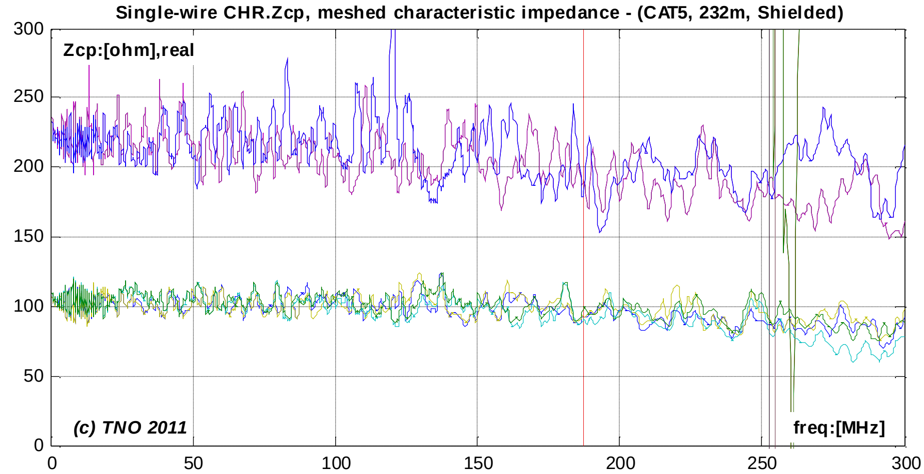


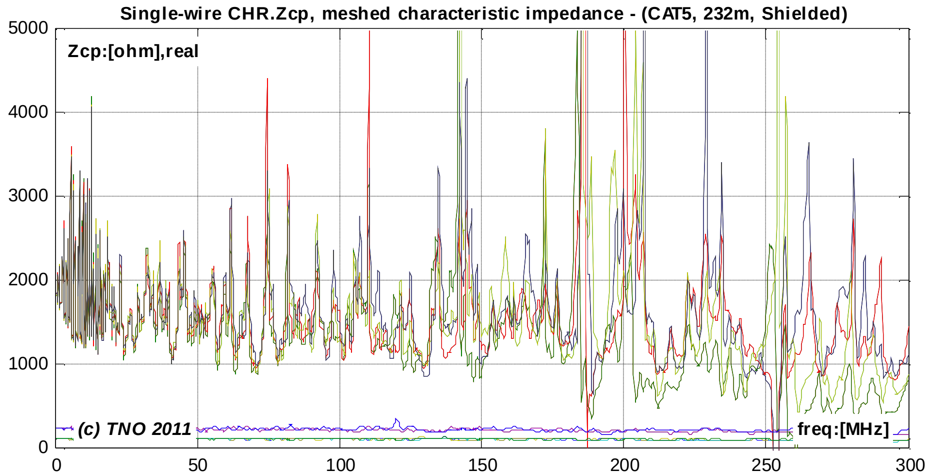


2.7.2 Equivalent circuit parameters (of single wires)

Another way to represent the (multiport) characteristic impedance is by means of an equivalent circuit diagram having the same z-parameters. The extracted impedances between the individual wires or the shielding is different for the various wires, and are shown in the figures below. An equivalent circuit that appoximates these impedances is also shown below. It has impedances of about 100 ohm (between wire and shield), 220 ohm (between twisted wires) and 1500 ohm or higher (between other wires).





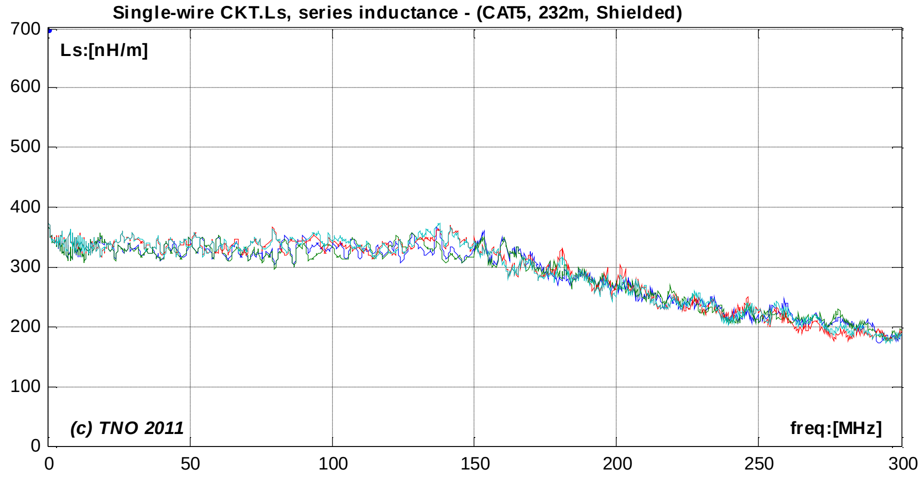


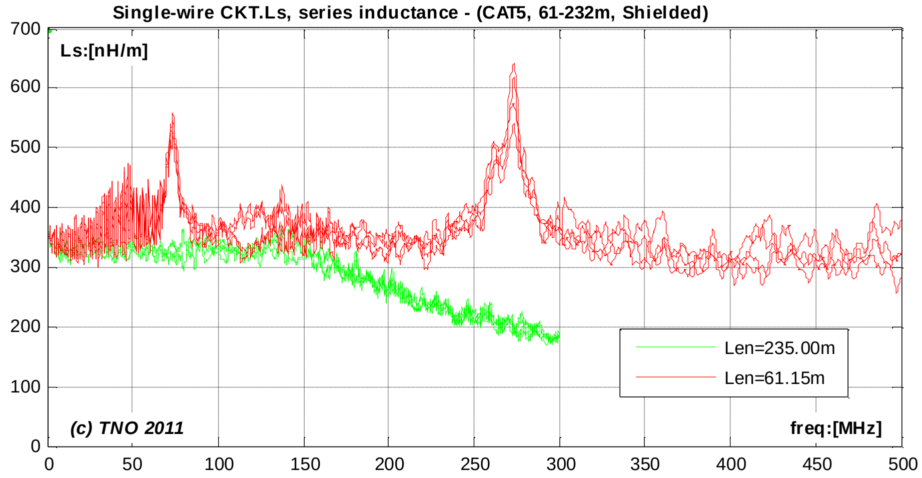
2.8 Primary cable parameters (single wires)

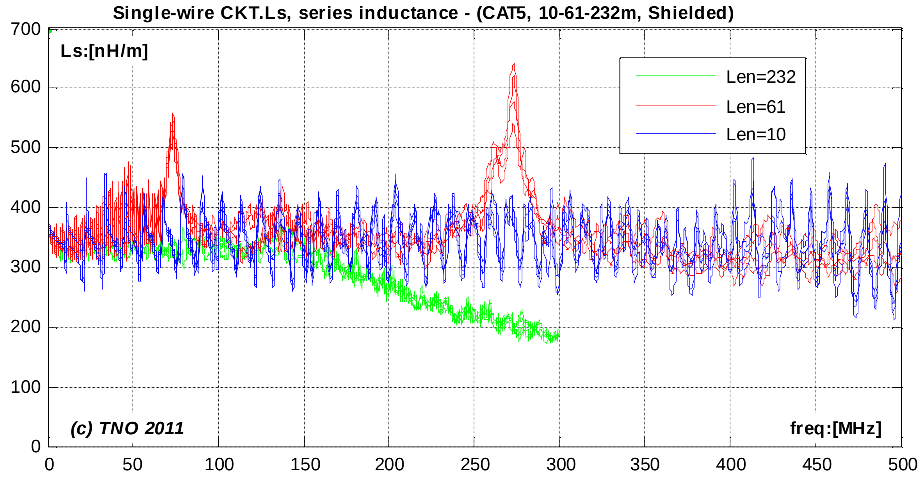
The extraction of primary (multi port) is a delicate mathematical process, where one solution is to be chosen out of an infinite number of possibilities. If the steps between succeeding frequencies in a sweep is too wide (compared to the loop length), then this extraction process may fail. Since the full mathematical details of this extraction is out of scope of this deliverable, we restrict ourselves to show the results.

2.8.1 Series inductance of individual wires

The extracted series inductance of each individual wire is more or less independent on the chosen wire. Roughly 330 nH/m for all wires in the “232m” section. The values extracted for frequencies above 150HMz should not be considered as reliable since the extractions failed for higher frequencies doe to too big steps in frequencies compared to the loop length.
Values extracted from shorter loops are more or less similar but suffer from unrealistic resonations. This problem has been explained before for the characteristic impedance, and worsens for shorter loops. Finding a solution for preventing this in the extraction is left for further study.

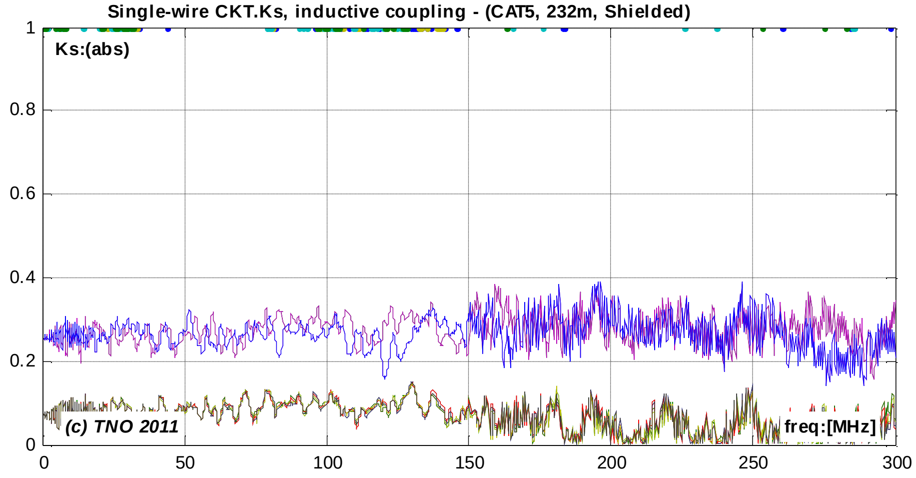

Single-wire CKT.Ls, series inductance - (CAT5, 232m, Shielded)
Ls:[nH/m]
(c) TNO 2011
freq:[MHz]
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300

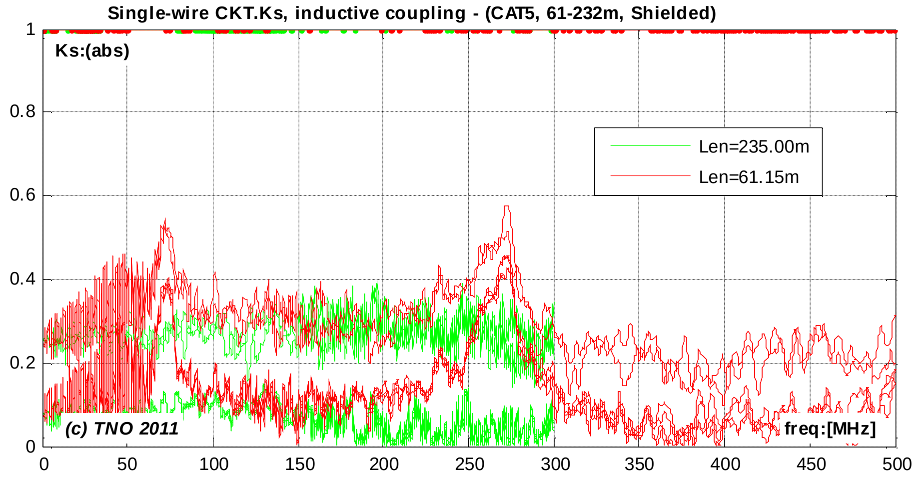

Single-wire CKT.Ls, series inductance - (CAT5, 61-232m, Shielded)
Ls:[nH/m]
Len=235.00m
Len=61.15m
(c) TNO 2011
freq:[MHz]
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
450
500

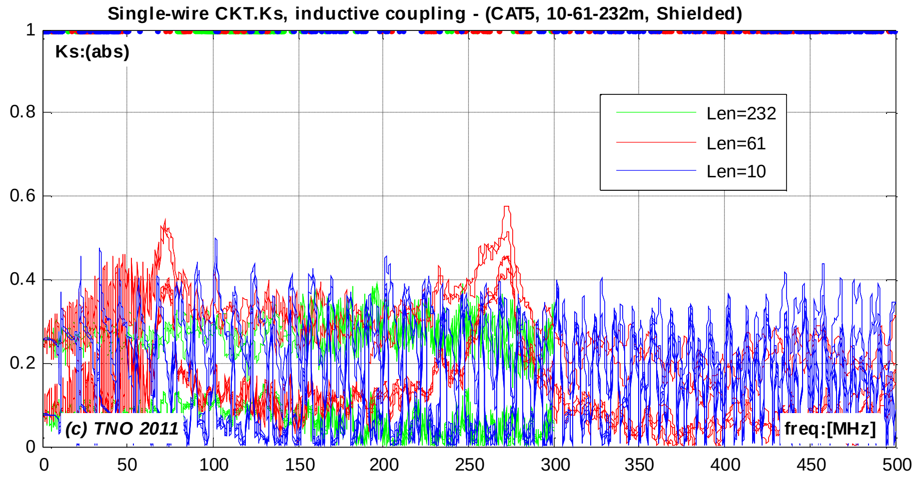

Single-wire CKT.Ls, series inductance - (CAT5, 10-61-232m, Shielded)
Ls:[nH/m]
Len=232
Len=61
Len=10
(c) TNO 2011
freq:[MHz]
700
600
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
450
500

2.8.2 Magnetic coupling between individual wires

The extracted magnetic coupling between the individual wires is different for the various wires. Values in the order of 0.26 hold between twisted wires, and 0.08 between other wires. Again the extracted values above 150HMz for the "232m" section should not be considered as reliable, nor the resonations in values for the shorter sections.

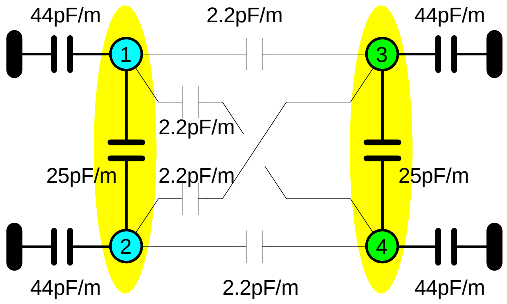


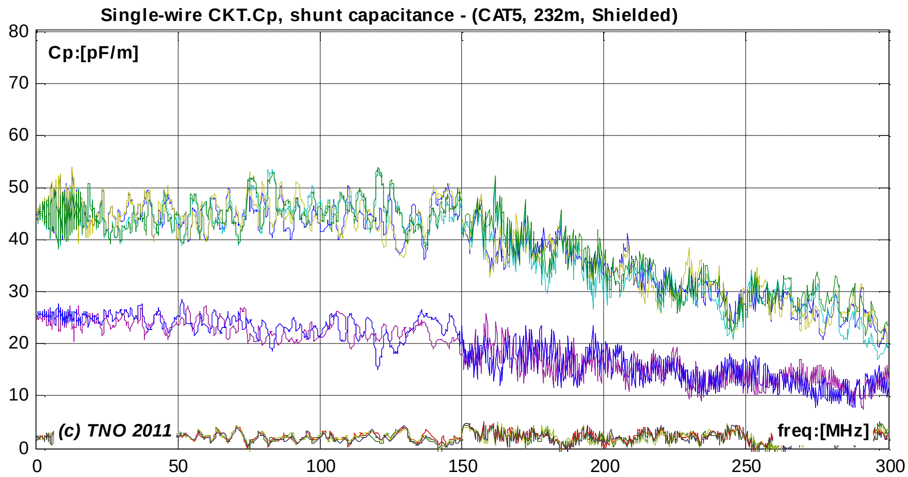


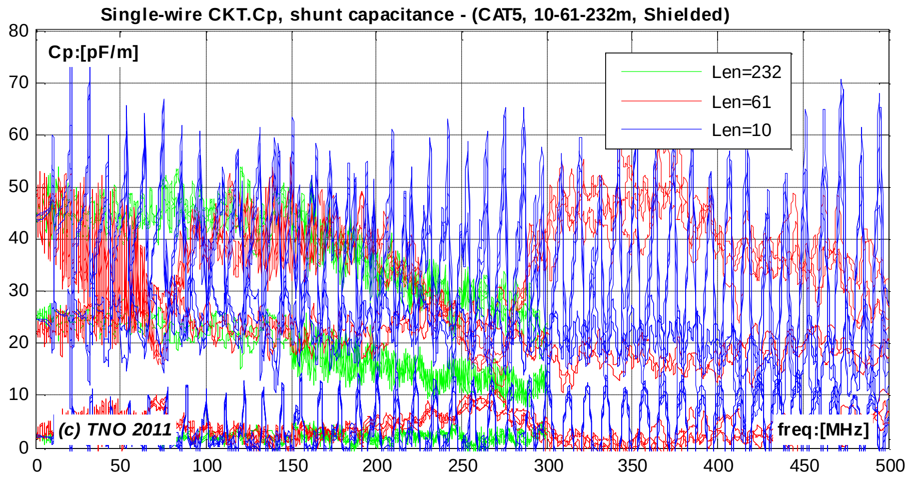


2.8.3 Shunt capacitance beween individual wires and/or shielding

The extracted shunt capacitance between the individual wires or the shielding is different for the various wires, and they are shown in the figures below. The extracted capacitances between the individual wires or the shielding is different for the various wires. An equivalent circuit that appoximates these shunt capacitances is shown below. It has capacitances of about 44pf/m (between wire and shield), 25 pF/m (between twisted wires) and 2.2 pF/m (between other wires).







3 MEDIUM QUALITY CABLING FOR TELEPHONY

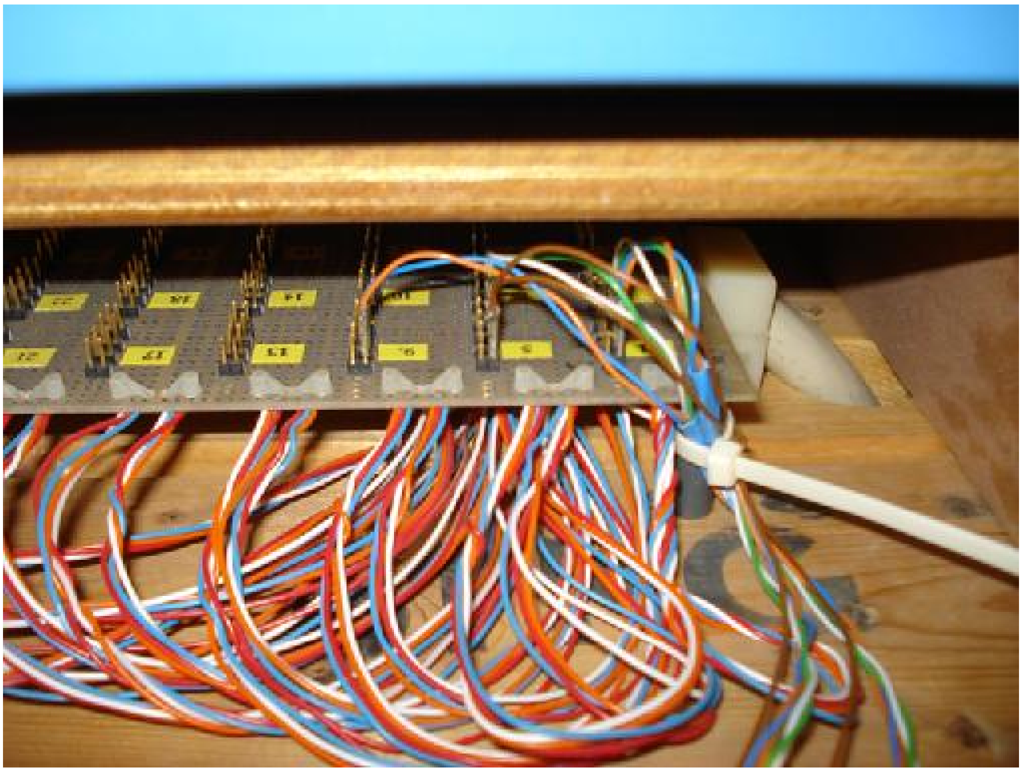
Another cable being characterized is a cable with 30 twisted quads (each with two wire pairs or 4 wires) and a common shielding. It is a cable with medium quality twists, so that crosstalk between other wire pairs is kept to a minimum. This cabling is typically used in buildings for offering telephony services to different locations in that building.

3.1 Description

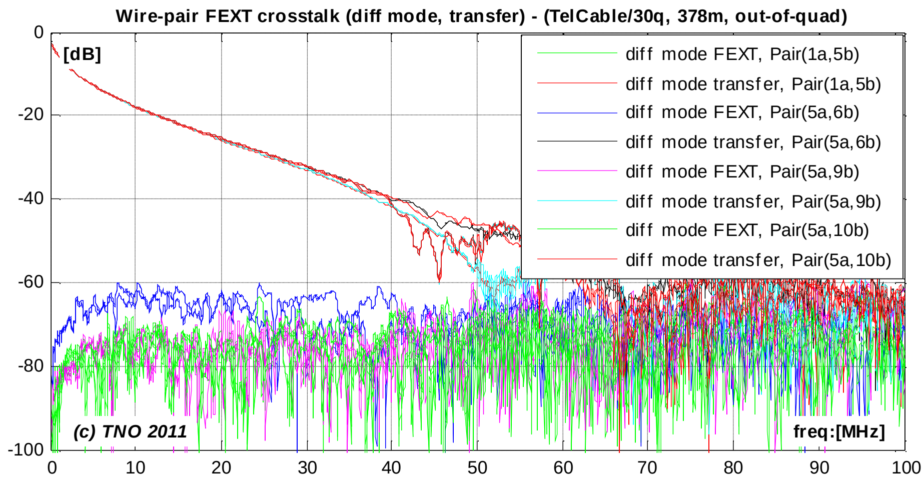
A long cable was made available on a huge drum, as shown at the pictures below. The actual length of this cable is unknown but we found different (conflicting) answers via different manners.

- Historical data indicated that the drum was filled with about 525m and that about 360m might be left after removing some cable length from the drum.
- We measured a loop resistance of a wire pair at 2*31.8 ohm, and by assuming 0.168145 ohm/meter loop resistance (a value that is commonly used for 0.5mm telephony wiring and also used in the “KPN_L1” model), the loop length is estimated at 378m.
- A geometric calculation, as elaborated at the end of this paragraph, indicated a length of about 388m.

As a result, we selected the middle one of these three by assuming **378m** for this cable. Transmission measurements showed afterwards that this length yields a velocity factor of 0.67 which is plausible.



The quads are terminated at an bread board for interconnection with the measurement setup, and the wire pairs to be characterized were selected at random so that in-quad as well as out-of-quad combinations of wire pairs are in the selection.
As shown on the pictures below, the bread boards are wired a bit chaotic manner, but this is considered as realistic in practical telephony wiring situations.
Measurements were elaborated up to 100 MHz, but the figure below illustrate that transmission gets useless above 40-50MHz since it will then get as worse as the FEXT. Therefore this cable is characterized up to 40MHz.



3.1.1 Length estimation via a geometric calculation.

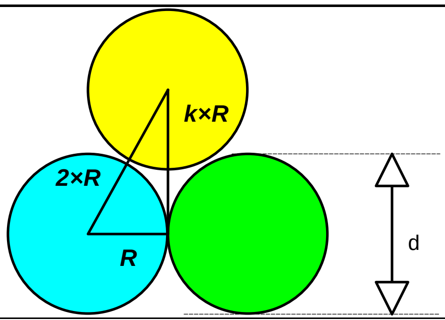
The figures below show the geometry of the cable on the drum how dense they may be packed together on the drum. This packing is to calculate the mean height of a single layer of cable. Calculating the total length is now given by the following steps:

mean thickness per layer	: $d_{layer} = \frac{d}{2}\sqrt{3} = 1.56\ cm$
number of layers	: $N_{layers} = \mathrm{int}\left(\frac{r_1 - r_0}{d_{layer}}\right) = 8$
mean windings per layer	: $W_{layer} = \frac{w}{d} - 1 = 26.8$
mean radius	: $r_m = \frac{r_0 + r_1}{2} = 30.5\ cm$
cable length per layer	: $L_{layer} = 2p\ r_m W_{layer} = 51.4\ m$
total cable length	: $L = L_{layer} N_{layers} = 411\ m$

Observations on this calculation and the actual drum lead show:

- The actual drum shows that the top-layer is only filled for 70%, giving N_{layers}=7.7.
- The number of windings per layer must be a half less than the originally calculated W_{layer} because an optimal layer with W_{layer} windings is followed by a shifted layer with one winding less.

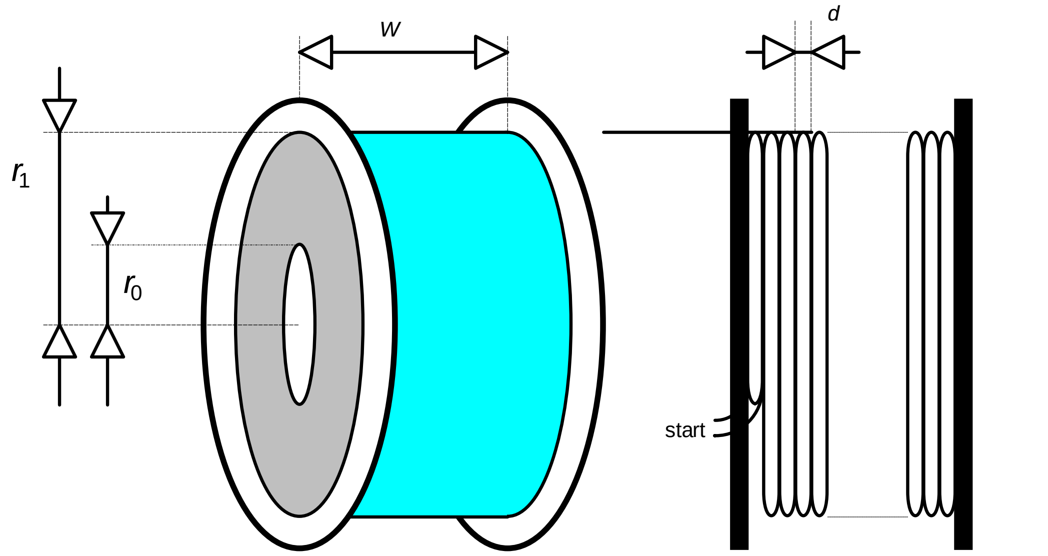
This leads to 388 m. Because this result is based on an optimal dense packing of the cable on the drum, which is not the case in practice, the actual cable length may even be a few meters less.



Factor *k* equals:

$$(2R)^2 = R^2 + (kR)^2 \quad \Rightarrow \quad k = \sqrt{3}$$

Fig: Cable diameter dimensions



r_o = 24 cm
r_1 = 37 cm
W = 50 cm
d = 1.8 cm

Top-layer is only filled for 70%

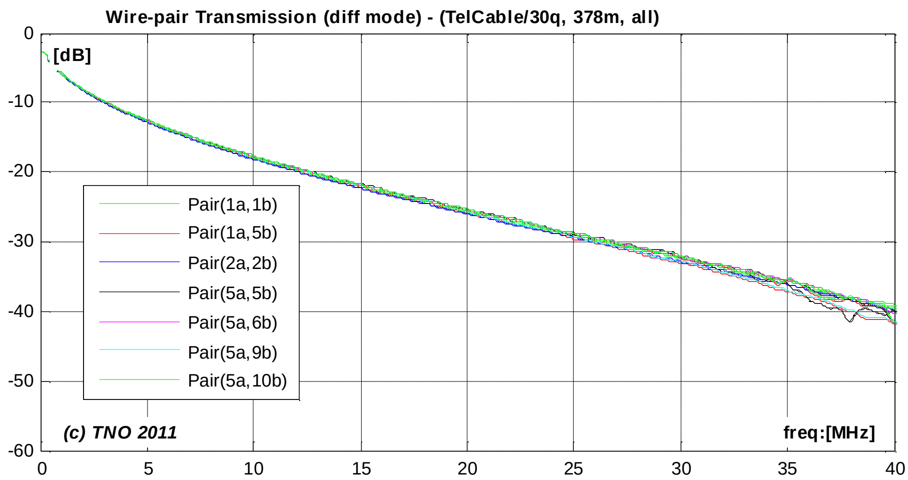
$W/d-1$=26.8

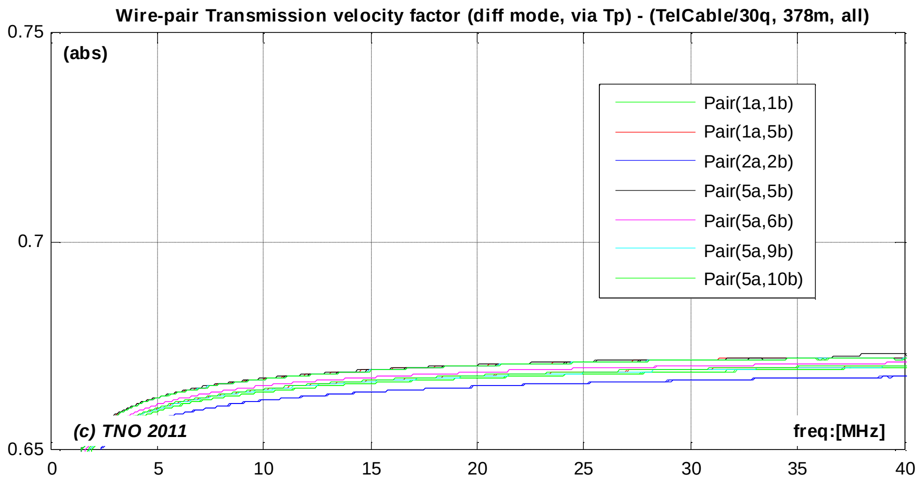
Fig: Cable drum dimensions

3.2 Transmission

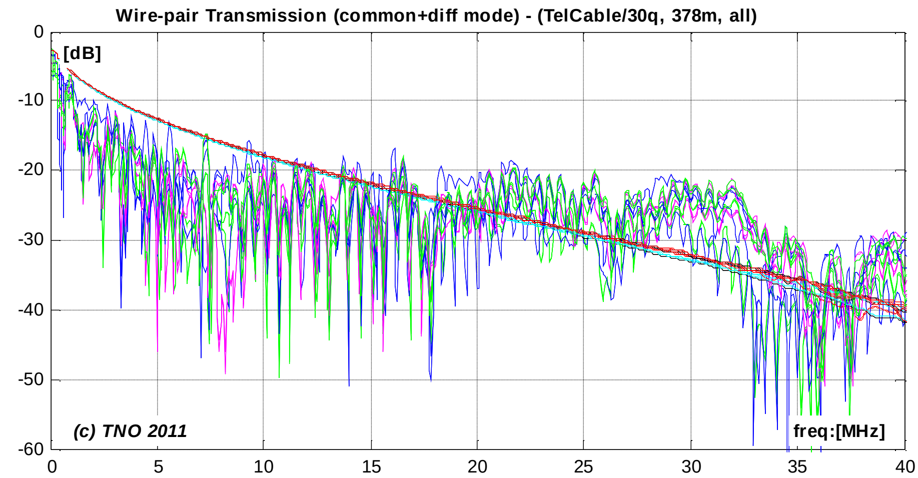
3.2.1 Differential mode

Differential mode transmission via this cable shows smooth curves up to 30MHz, and starts rippling above that frequency. This demonstrates the medium quality of this type of cabling, which is nevertheless excellent for transporting analog telephony signals. It learns that the typical insertion loss is **8.60dB** @ 30MHz @ 100m on average.
The observed velocity factors of all measure wire pairs is in the order of **0.67**.



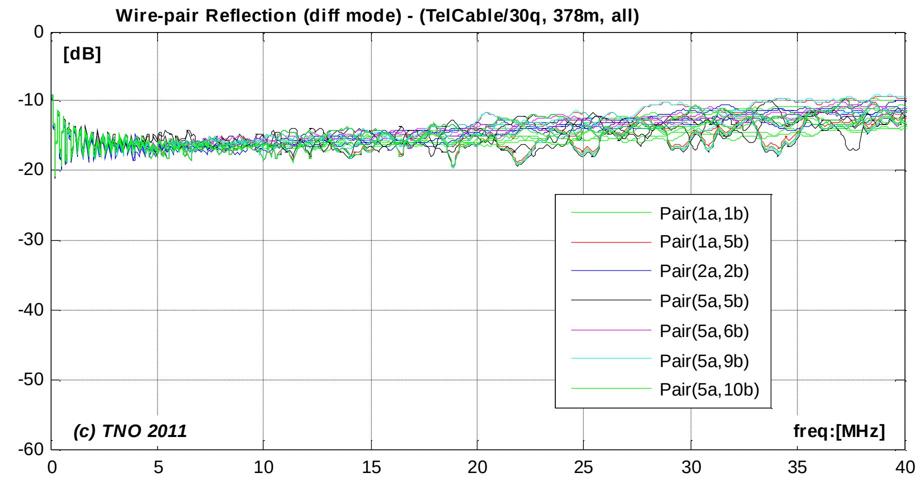


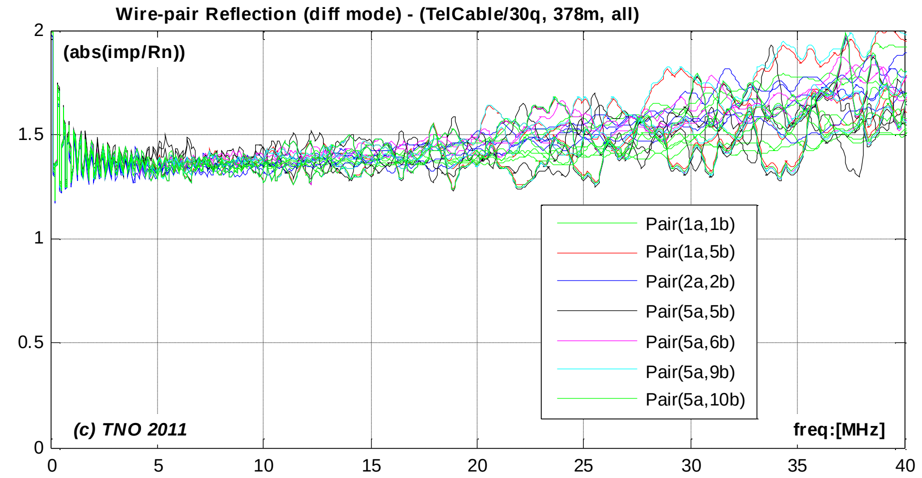
3.2.2 Common Mode



3.3 Reflection

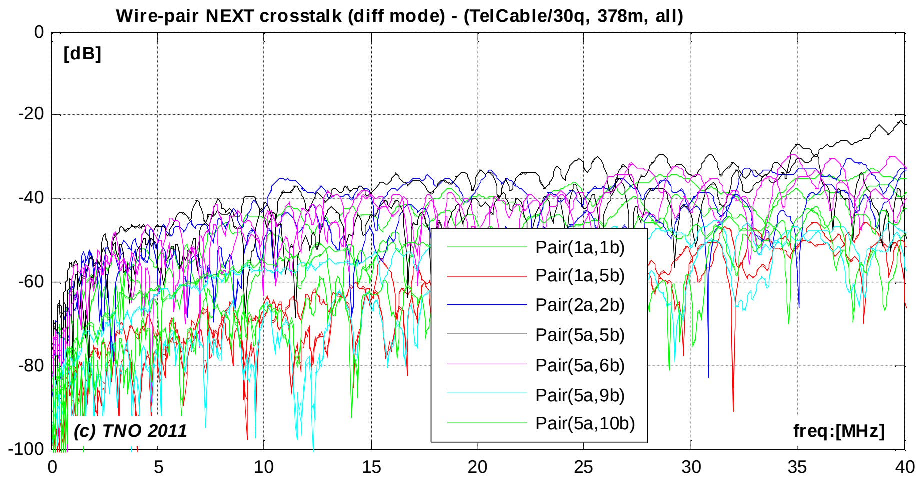
The differential mode reflection is related to the input impedance of the cable and the reference impedance (R_N) used for representing the measured s-parameters. Both are shown below. The input impedance is about 135Ω at low frequencies, and increases a bit towards higher frequencies. It is rather indifferent for the various wire pairs.

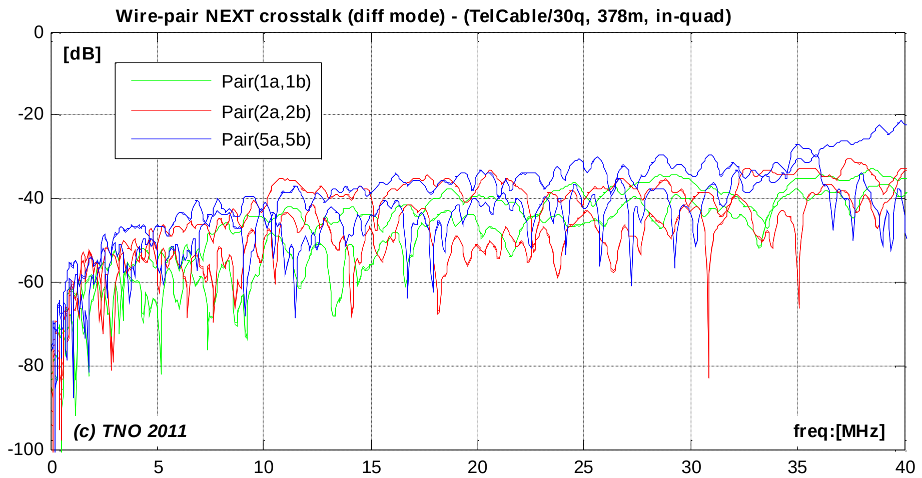


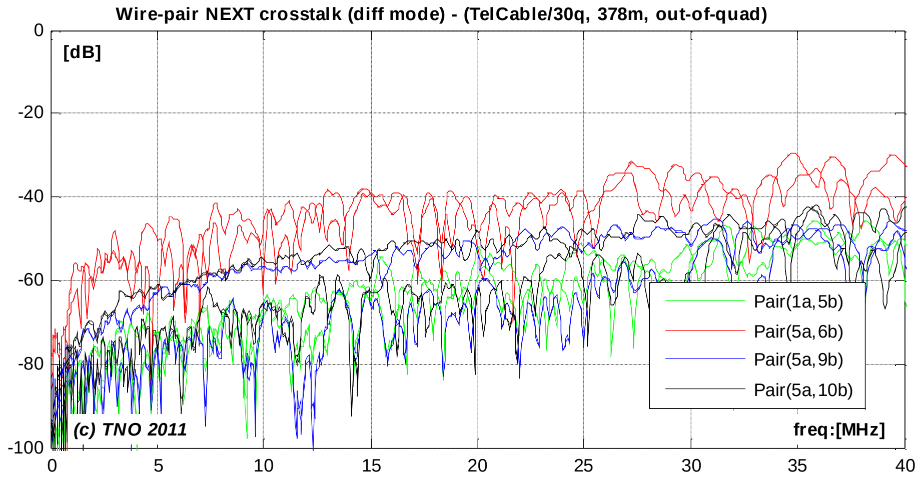


3.4 Near end crosstalk coupling (NEXT)

The differential mode NEXT is dependent on the selected wire pairs, where the observed out-of-quad NEXT are often lower than the observed in-quad NEXT. But this does not hold for the NEXT between pair 51 and 6b. This might be caused by the fact that their twist rotate in the same direction with the same pitch, so in general one cannot say that the in-quad NEXT is always higher than out-of-quad NEXT.



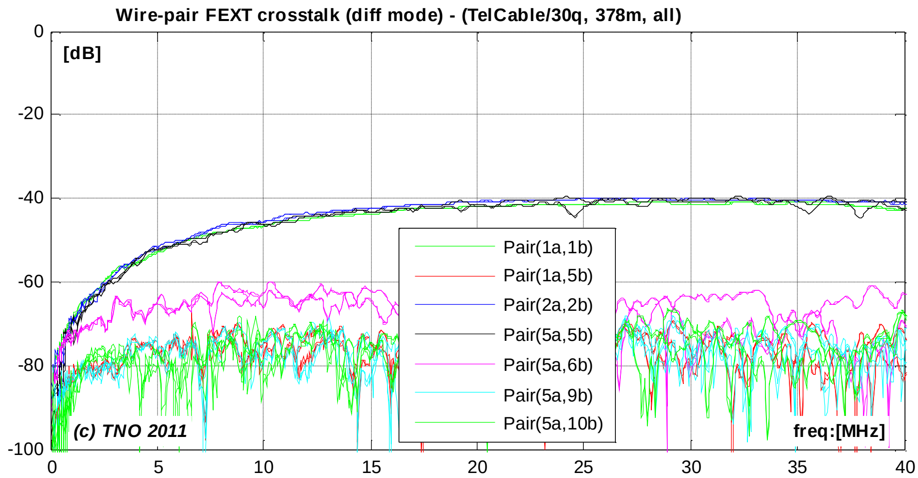


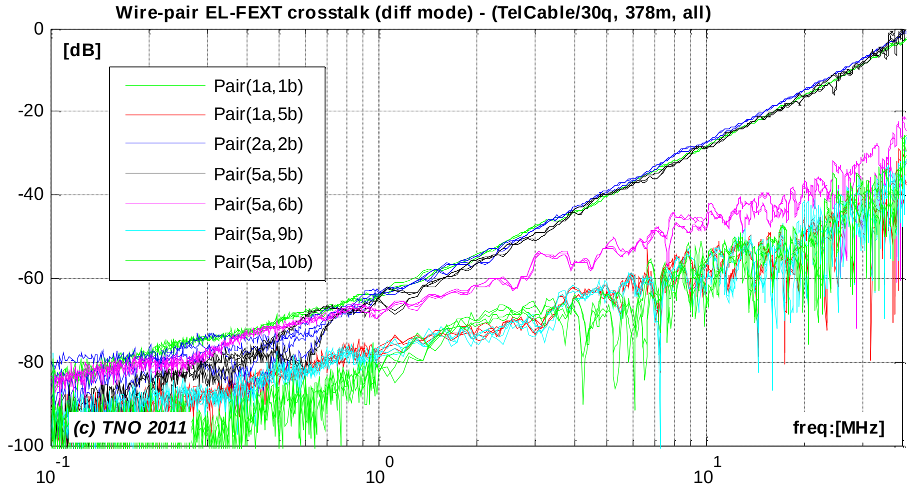


3.5 Far end crosstalk coupling (FEXT and EL-FEXT)

The observed differential mode FEXT between the in-quad wire pairs is always significantly higher than between the observed out-of-quad wire pairs. The in-quad FEXT coupling is almost deterministic in nature, which is not surprising since the wire pairs are grouped in a regular geometry over the full wire length.

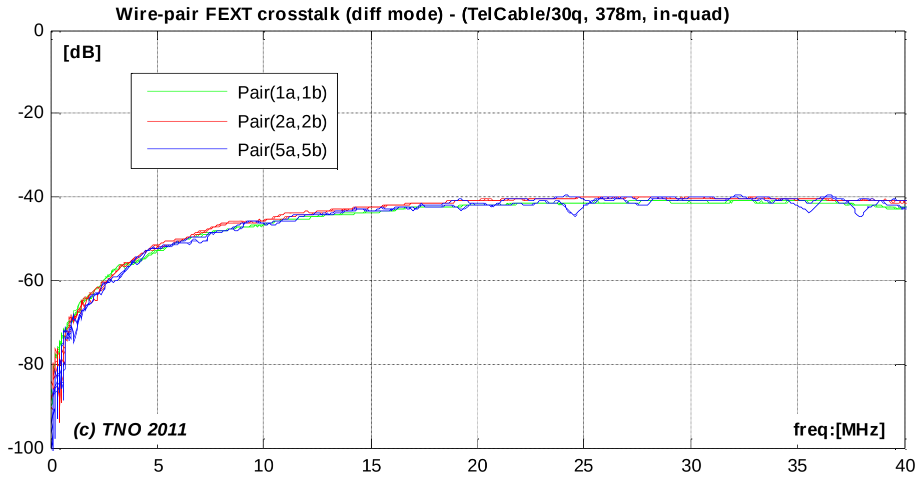
The EL-FEXT plot with logarithmic frequency scaling illustrates that EL-FEXT within the observed quads is capacitive in nature, and that this cannot be observed between the out-of-quad wire pairs (due to its low coupling values).

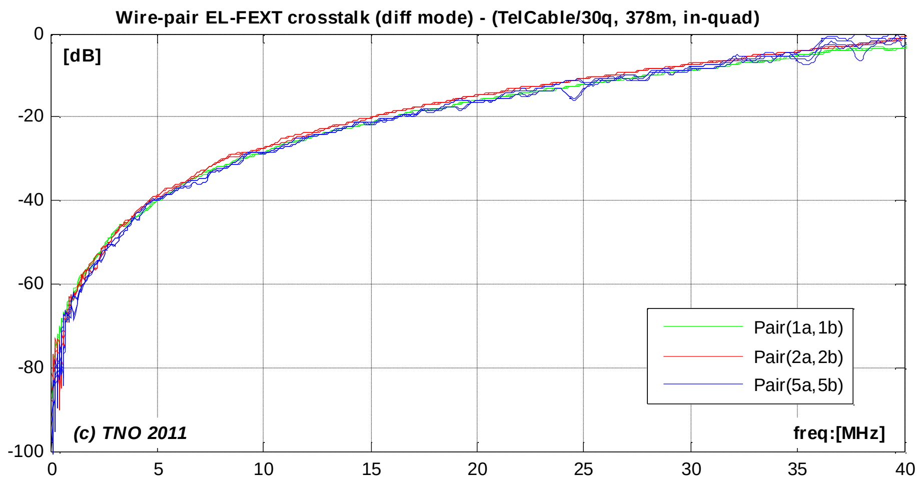


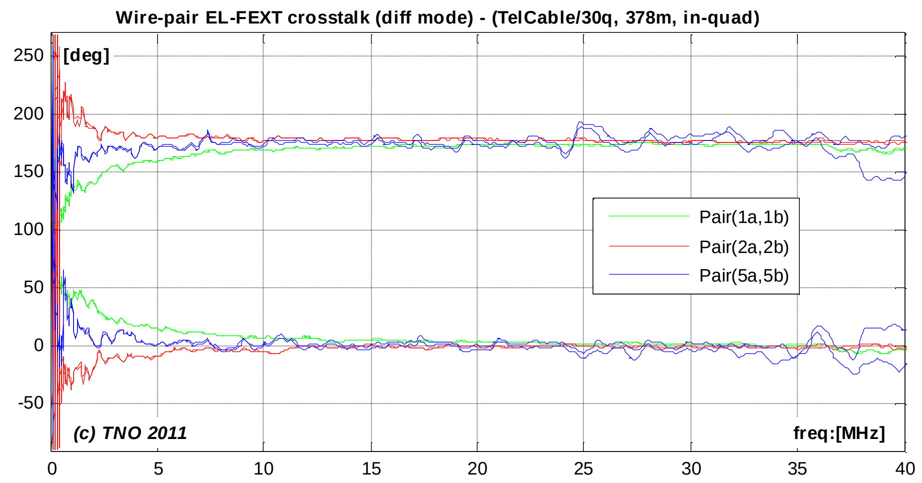


3.5.1 In quad FEXT

The observed in-quad FEXT as well as its EL-FEXT are shown in the figures below. The magnitudes of these FEXT curves are not only smooth in frequency but their real parts phase is also close to zero (positive sign) or 180 degrees (negative sign). This emphasizes the deterministic nature of the observed FEXT coupling.

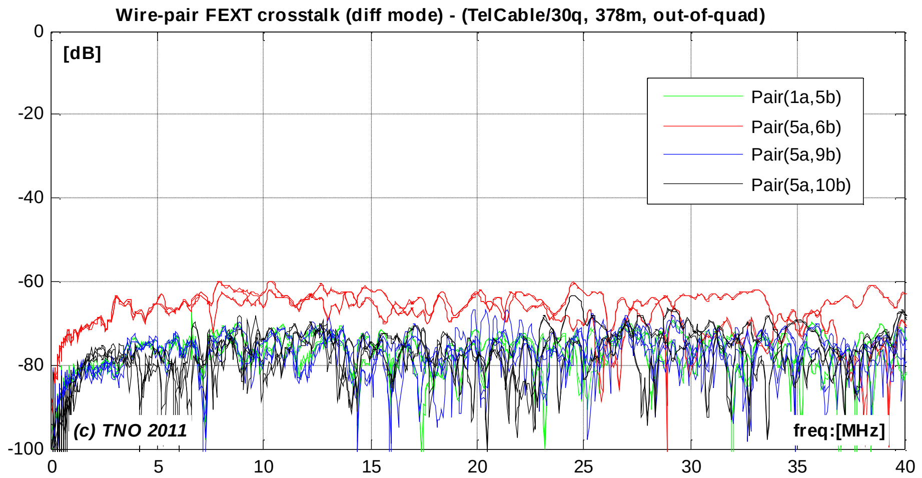


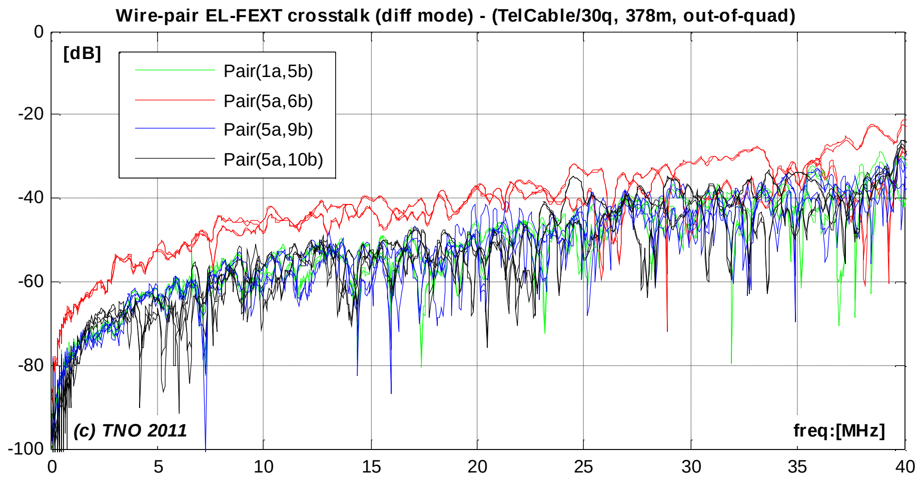


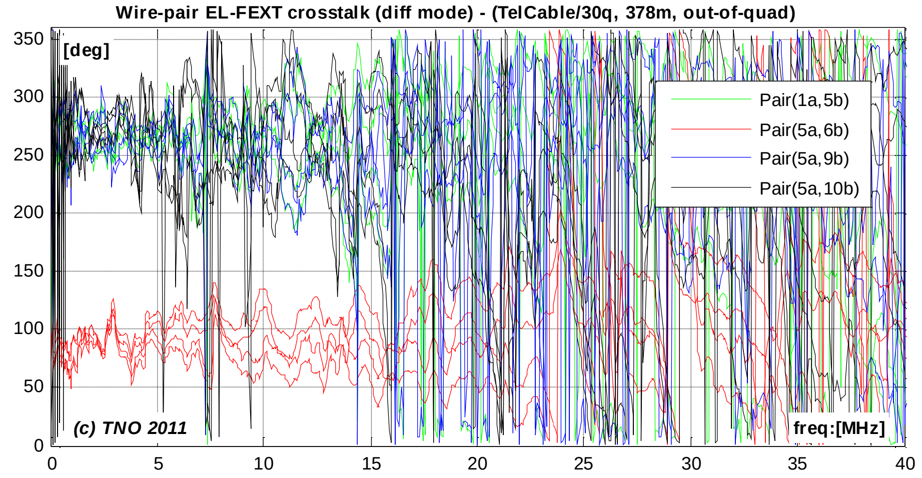


3.5.2 Out-of-quad FEXT

The observed out-of-quad FEXT as well as its EL-FEXT are shown in the figures below. The magnitudes of these FEXT curves are not smoothed in frequency but their real parts phase remain close to zero (positive sign) or 180 degrees (negative sign).



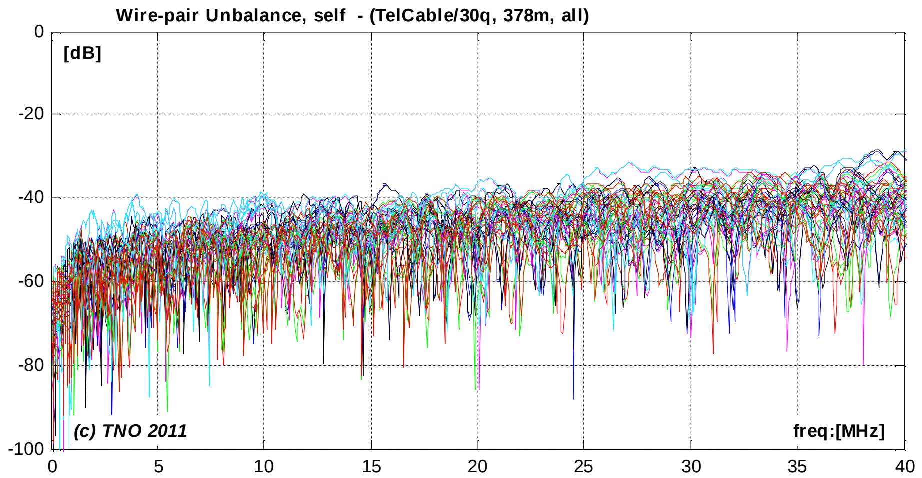




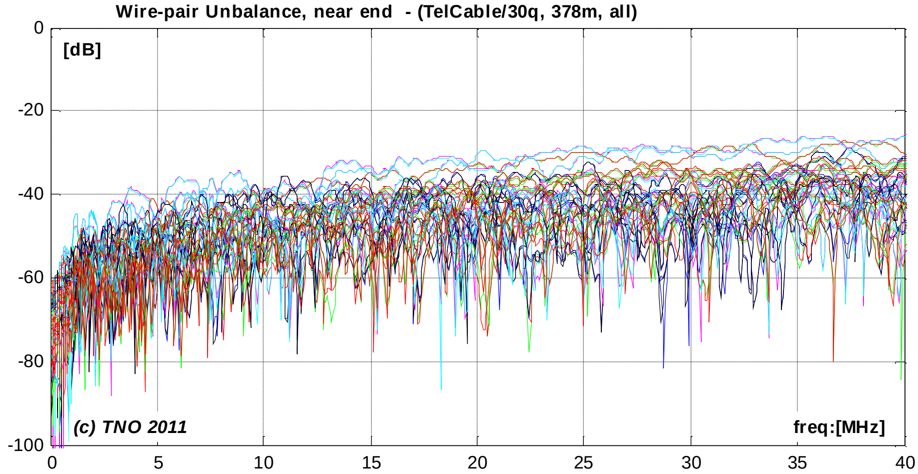
3.6 Unbalance

The unbalance of a cable expresses the conversion from common to differential mode if a common mode signal is injected, or the conversion from differential to common mode if a mode signal is injected. This is a reciprocal process, meaning that both conversion values are to be equal and the figures below illustrate how good this can be observed from the measurements.
The unbalance of all observed wire pairs is in the same order of magnitude, and therefore the different unbalance characteristics are shown for all wire pairs in the same plot.

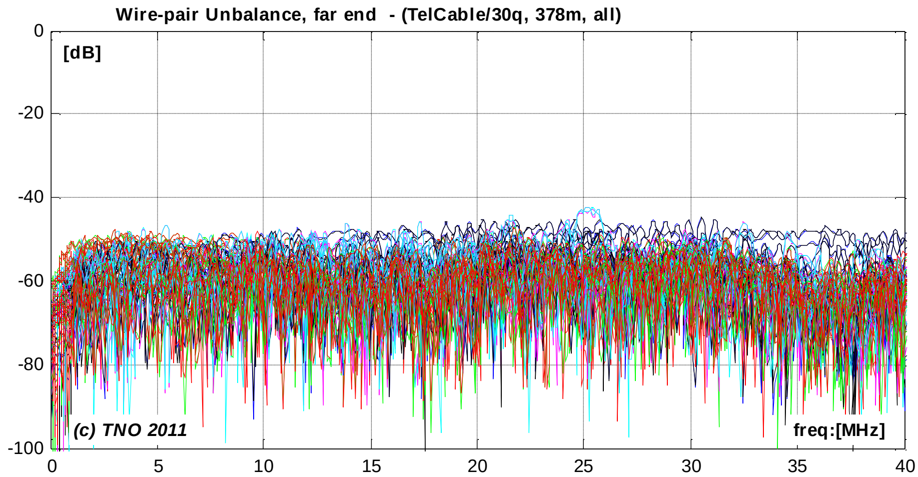
3.6.1 Self mode conversion



3.6.2 Near-end mode conversion



3.6.3 Far-end mode conversion

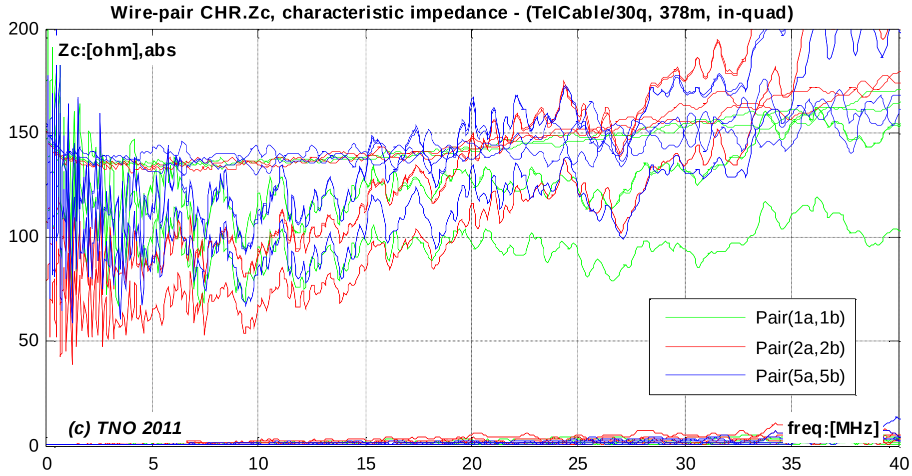


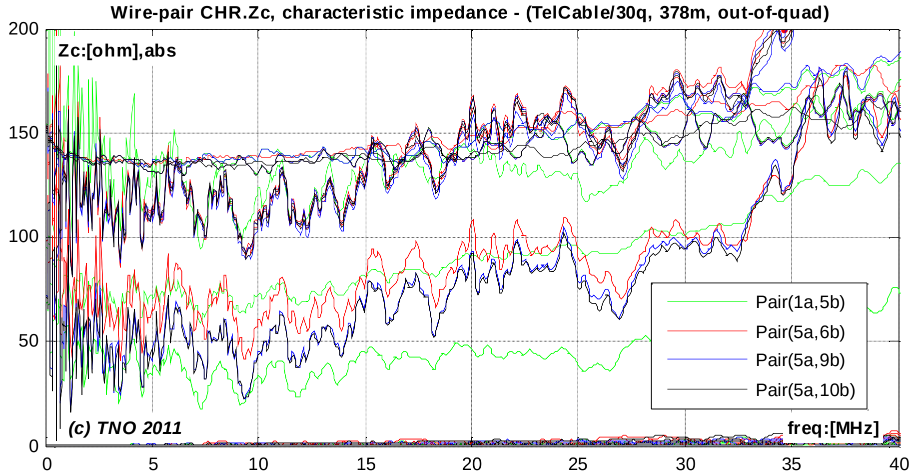
3.7 Characteristic impedance

The (multi port) characteristic impedance is indicative for the (multi port) input impedance of a very long loop. This multiport impedance can be represented by means of a matrix-representation (z-parameters are convenient for matrix calculations) and by means of an equivalent circuit representation (convenient for physical interpretation). Both are shown below.

3.7.1 Matrix parameters (of wire pairs)

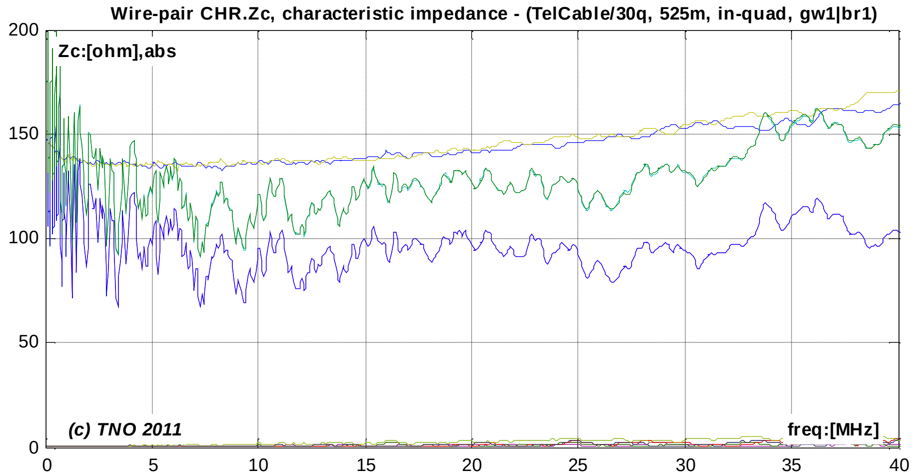
The multi-port matrix parameters for the in-quad wire pairs are a bit different of those for the out-of-quad wire pairs. Both are shown below in different figures. These curves are a combination of the differential mode Z_c, the common mode Z_c (which are a bit lower) and other coefficients. There values are a bit different fort he different combinations, but the example for an in-quad wire pair shows a pattern in these values.





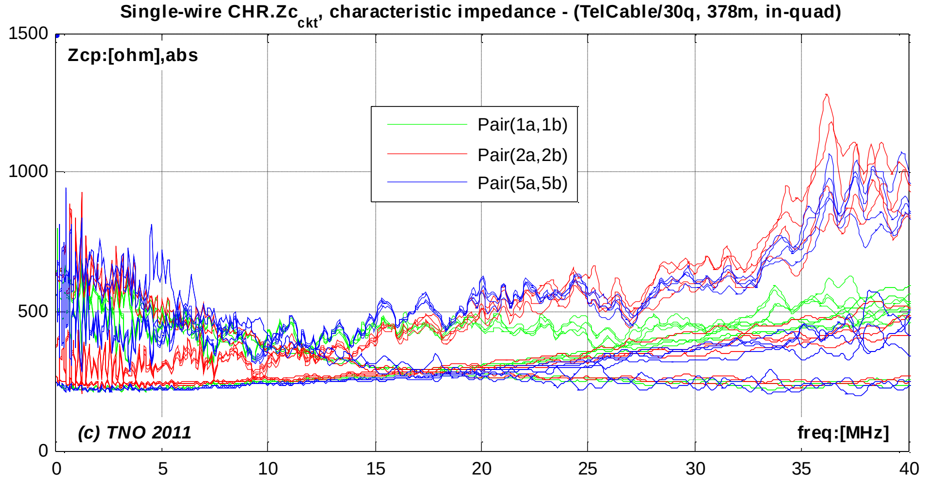
When we look at an in-quad example (gw1|br1), then the following can be observed.

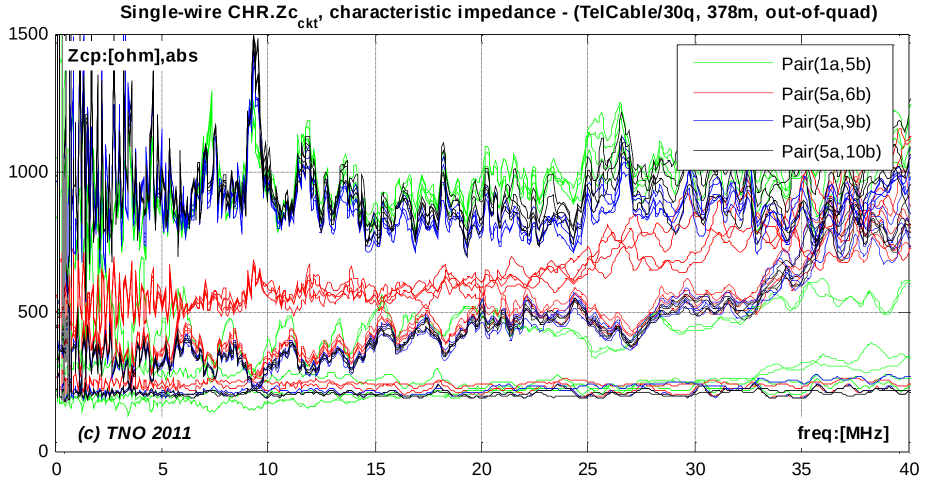
- The two upper (smooth) curves, around 135ohm, represent the differential mode Z_c.
- The two middle(rippling) curves, around 120 and 100 ohm, represent the common mode Z_c.
- All the other (lower) values are the remaining coëficients of the (mixed mode) characteristic impedance matrix. Their meaning is more mathematical in nature.

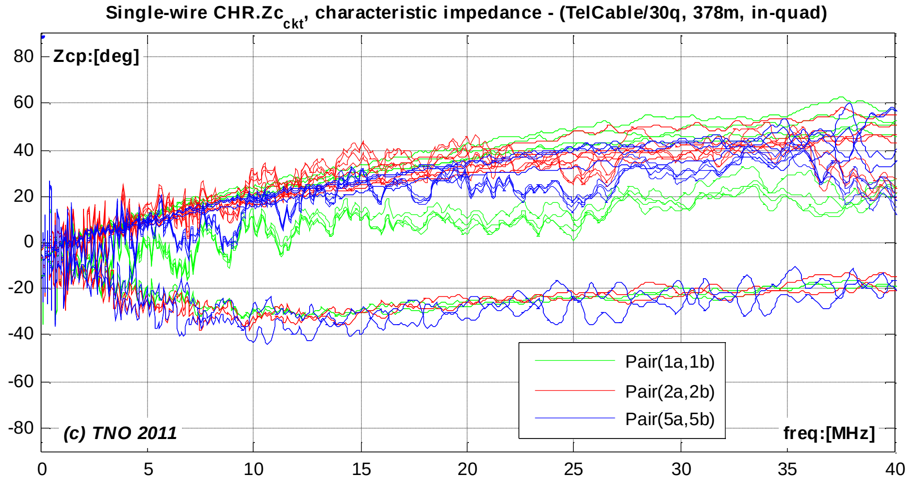


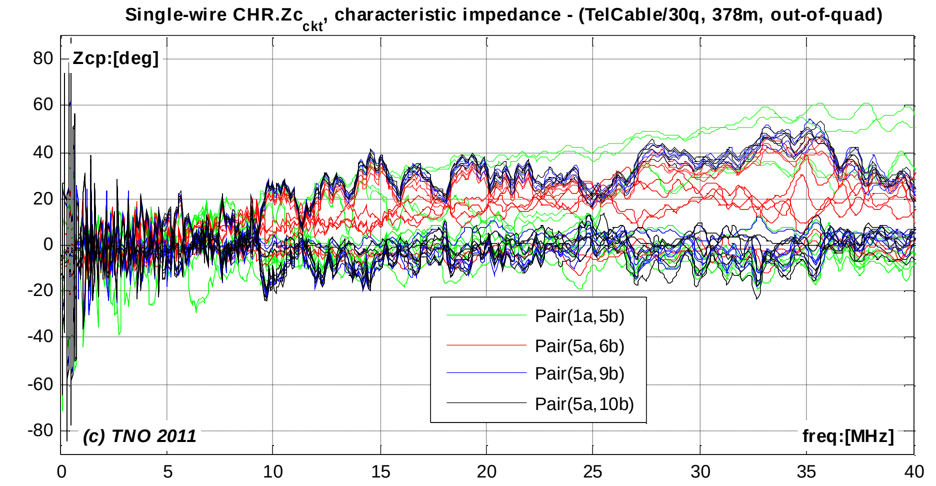
3.7.2 Equivalent circuit parameters (of single wires)

Another way to represent the (multiport) characteristic impedance is by means of an equivalent circuit diagram having the same z-parameters. The extracted impedances between the individual wires or the shielding is different for the various wires, and are shown in the figures below.
The in-quad combinations have a similarity and the out-of-quad combinations as well. The phase curves show that in all cases the values of these impedances are dominated by their real parts (especially for the out-of-quad combinations).

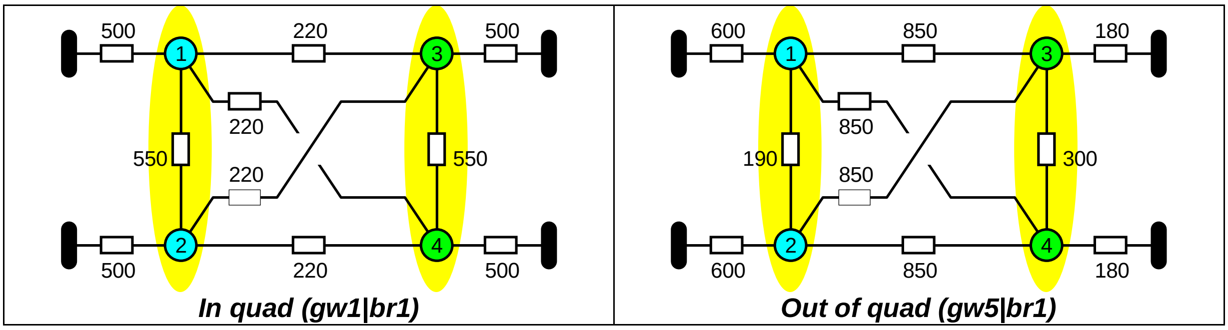


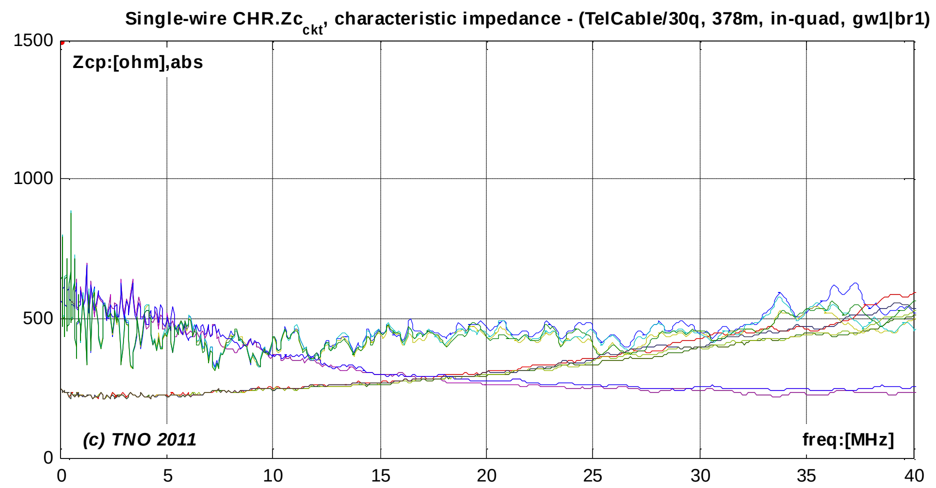


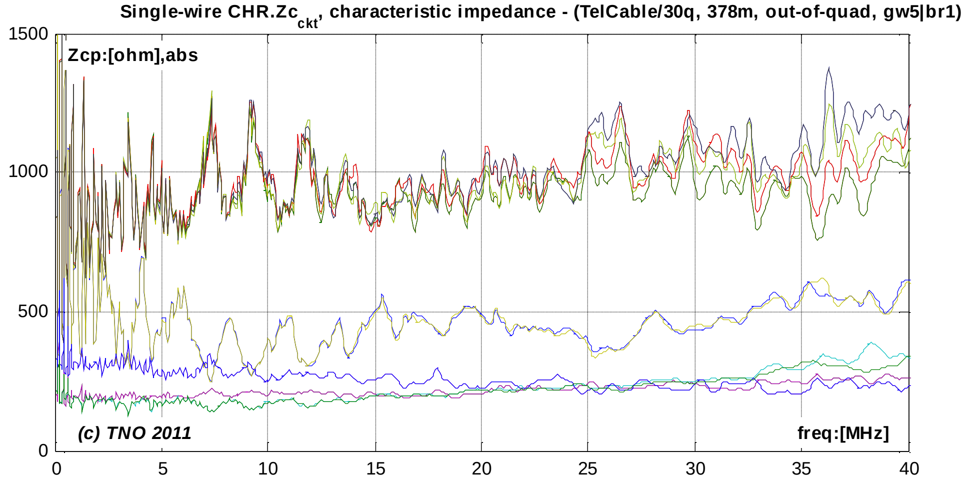




Typical impedance values becomes visible when we concentrate on few examples. The plots below show an in-quad and an out-of-quad example. The impedances are somewhat frequency depended, but if we concentrate on lower frequencies then the following circuit diagrams are indicative for these two examples.
Impedances to the shielding can be low as well as (relatively) high, and the same applies for the cross impedances.



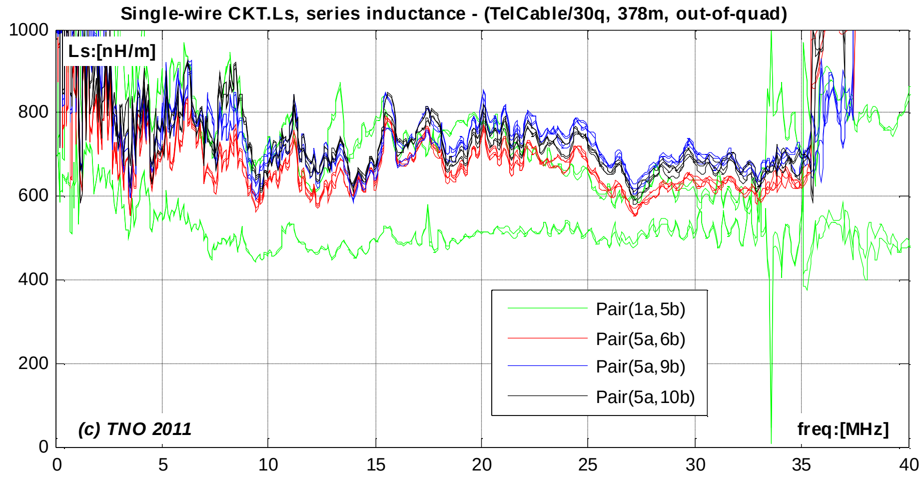


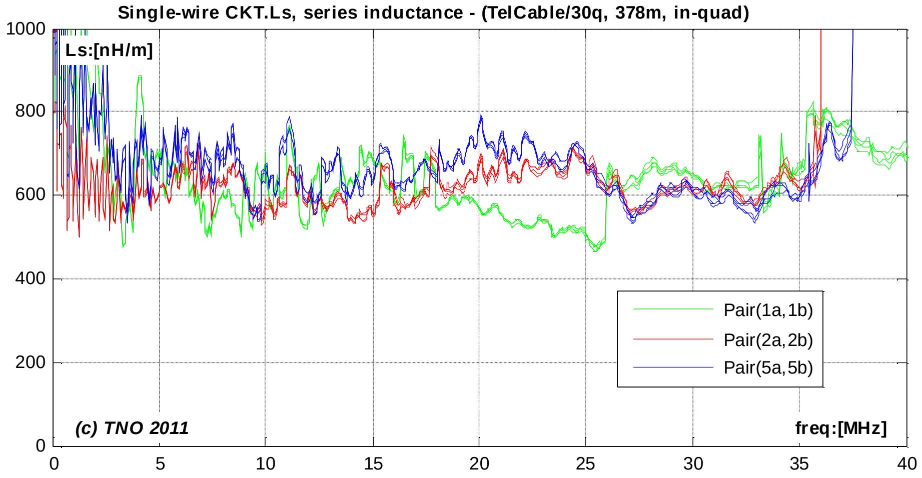


3.8 Primary cable parameters (single wires)

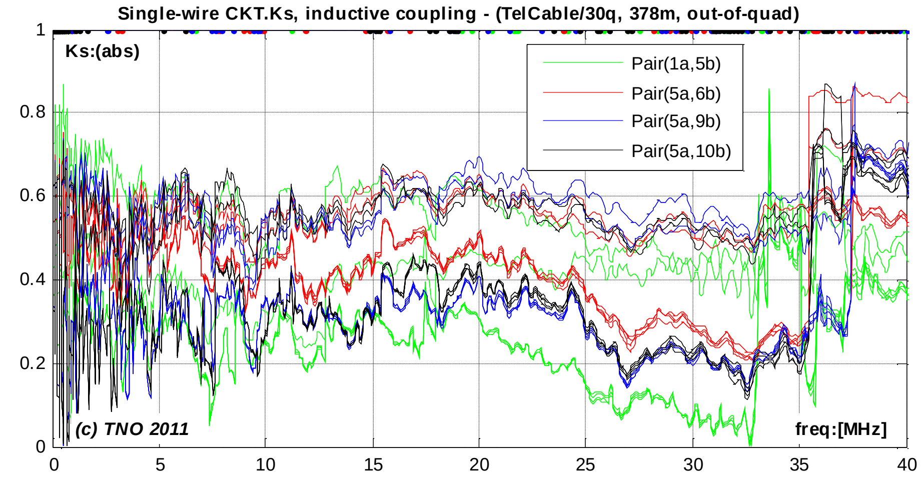
The extraction of primary (multi port) is a delicate mathematical process, where one solution is to be chosen out of an infinite number of possibilities. If the steps between succeeding frequencies in a sweep is too wide (compared to the loop length), then this extraction process may fail. Extraction of the characteristic coefficients (wich serves as an intermediate step) of this cable showed that the phase of the current extraction becomes unrealistic beyond 18 MHz. Since the full mathematical details of this extraction is out of scope of this deliverable, we restrict ourselves to show the results. The extracted curves are shown below.

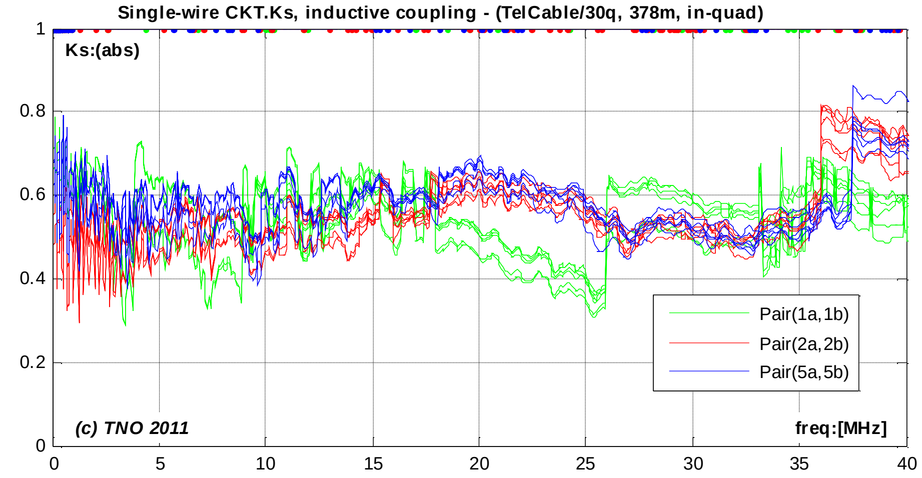
3.8.1 Series inductance of individual wires



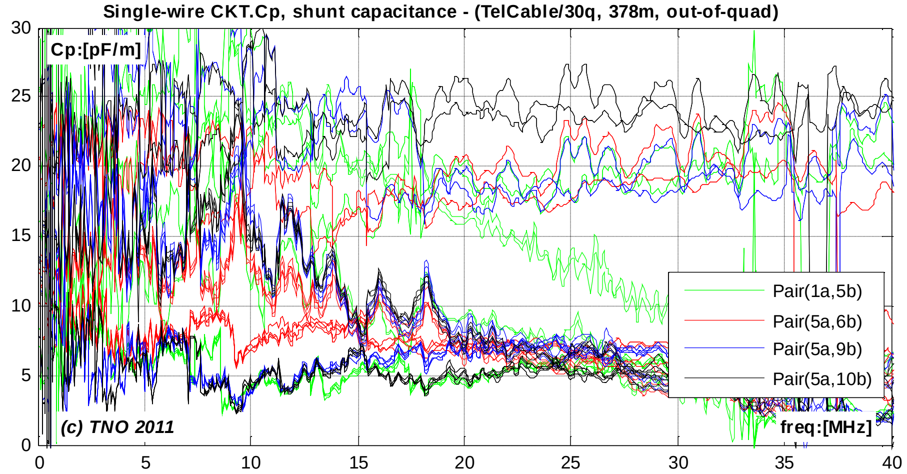


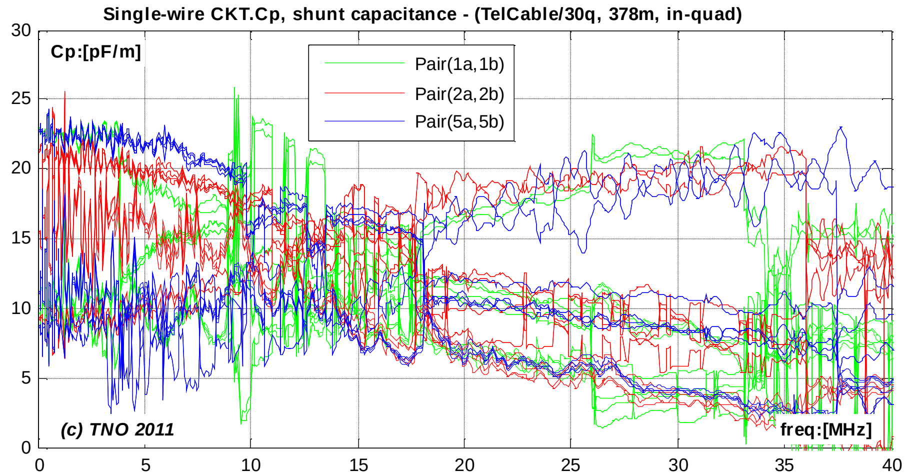
3.8.2 Magnetic coupling between individual wires





3.8.3 Shunt capacitance beween individual wires and/or shielding





4 LOW QUALITY CABLING FOR TELEPHONY

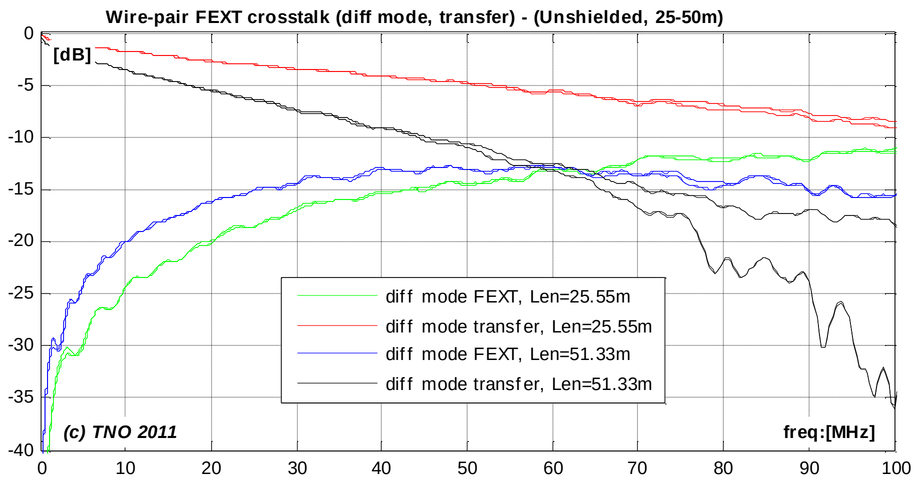
Another cable being characterized is the kind of cabling found in consumer shops ("Gamma" in this example), being sold as "telephony cabling". In general these cables are of undefined quality. Due to the lack of any twisting, and due to the irregular geometry of the distance between the wires, it may not be of any surprise that the quality of this cabling is very low. The measurements in this chapter demonstrate how low this may be in practice.

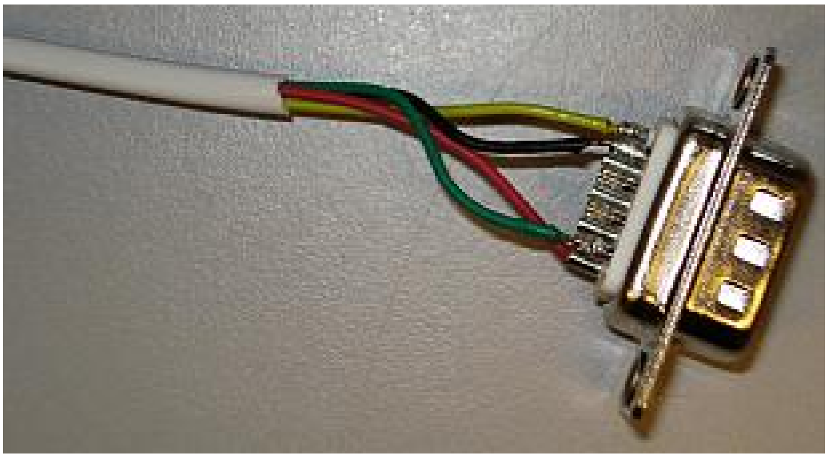
4.1 Description

The "Gamma" cable has 4 wires, has no shielding at all and the wires are hardly twisted. Therefore a common return path, following the same path as the forward path was not possible. Common was therefore undefined (and return currents flew via the instrument), making the measurement less accurate.

Two length have been characterized, a section named "25m" being 25.55m in length and a cascade section named "50m" being 25.55+25.78=51.3m in length. But due to the elastic nature of cabling, this length isn't reproducible up to a precision of 1cm.
Since the cable was unshielded, it was unrolled and laid down on the floor to prevent parasitic crosstalk.

Measurements were elaborated up to 500 MHz, but the figure below illustrate that transmission in the "25m" section becomes useless above 120MHz since it will then get as worse as the FEXT. The same applies above 55MHz in the "50m" section. Therefore the characterization of this cable is shown up to 100MHz during the rest of this chapter.

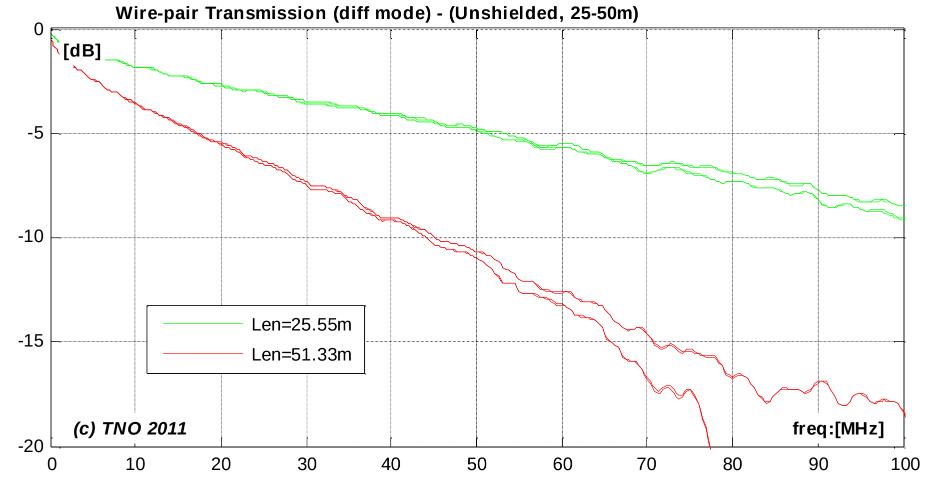


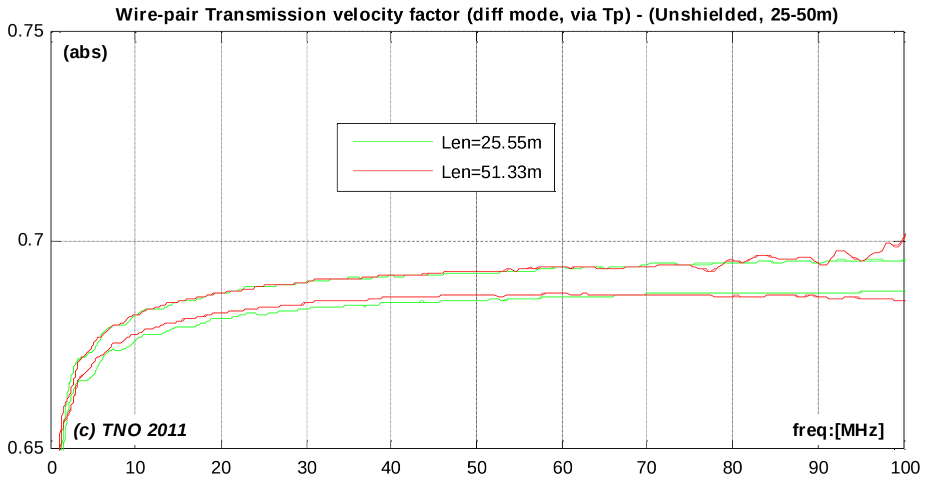


4.2 Transmission

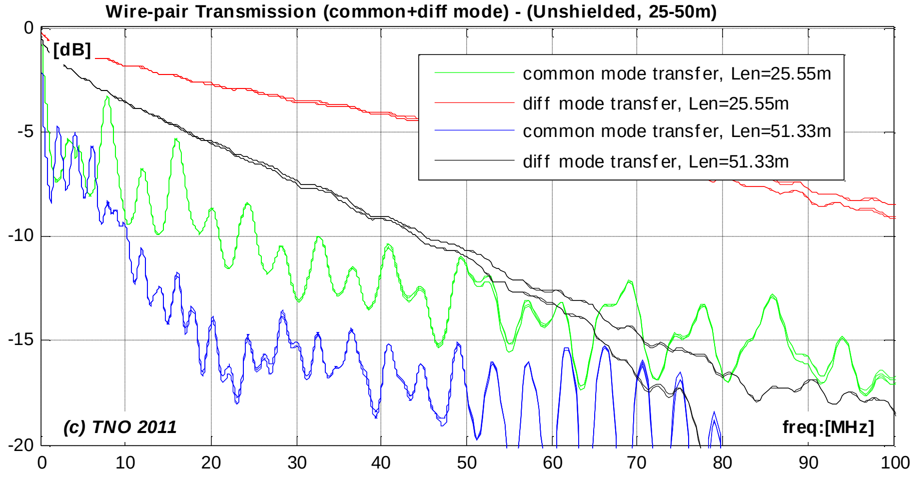
4.2.1 Differential mode

Differential mode transmission via this cable shows reasonable smooth curves up to 100MHz. It learns that the typical insertion loss is **14.46dB** @ 30MHz @ 100m. The observed velocity factor is in the order of **0.69**, which is considered as typical for these types of cabling. The spread in velocity factor between the wire pairs is less than 1%, which can be explained by assuming that the different wire pairs are not perfectly equal in length.



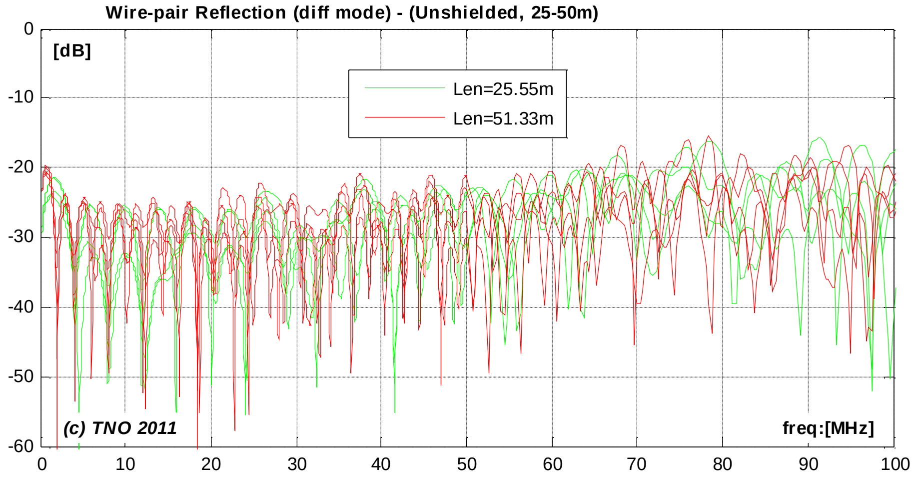


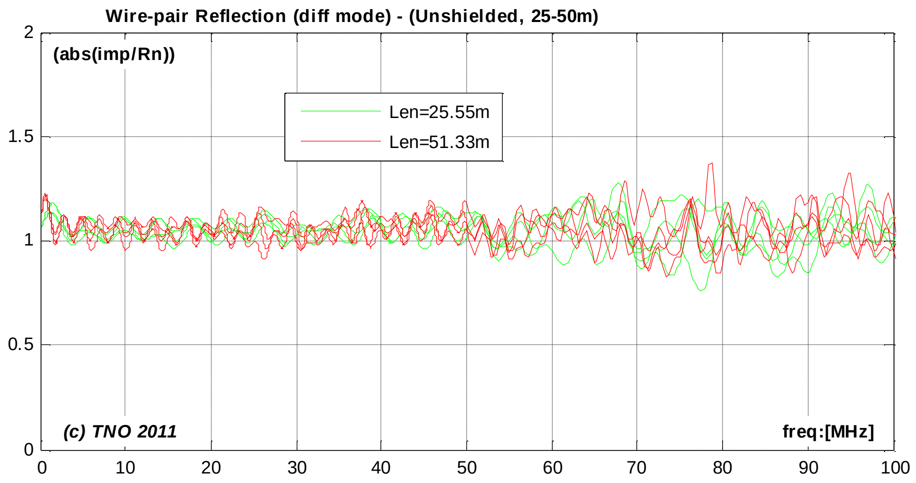
4.2.2 Common Mode



4.3 Reflection

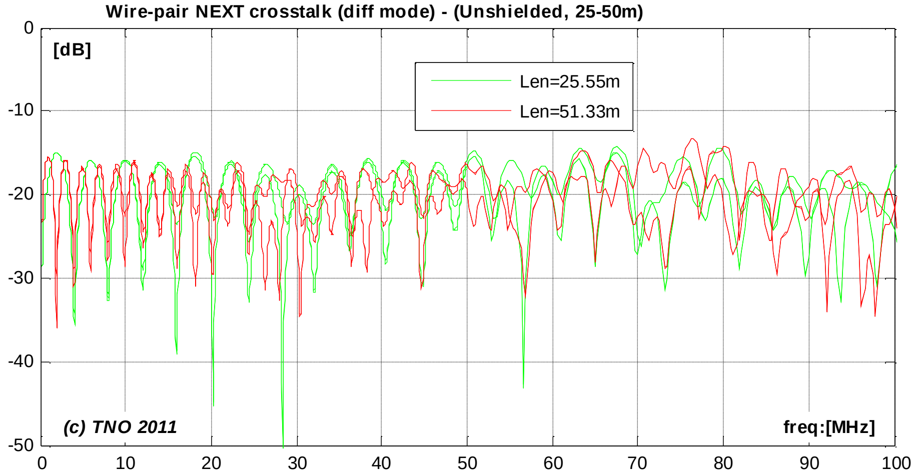
The differential mode reflection is related to the input impedance of the cable and the reference impedance (R_N) used for representing the measured s-parameters. Both are shown below. The input impedance is about 105Ω at low frequencies, and increases a bit towards higher frequencies. It is rather indifferent for the various wire pairs.





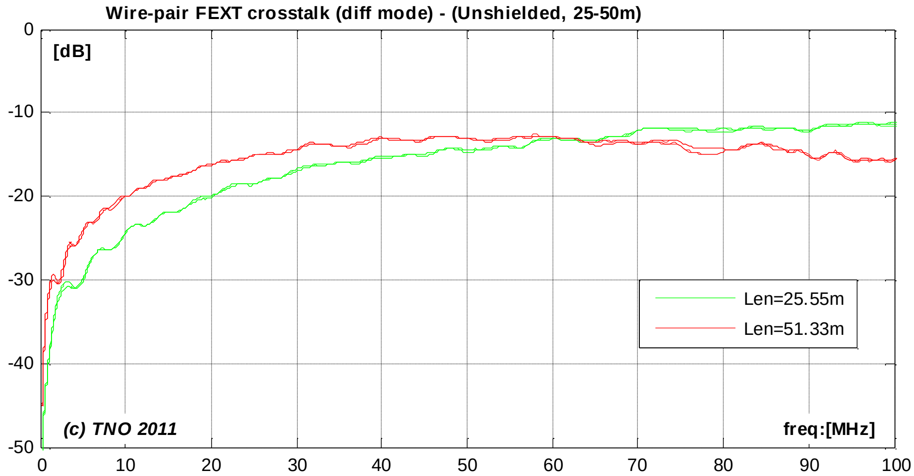
4.4 Near end crosstalk (NEXT)

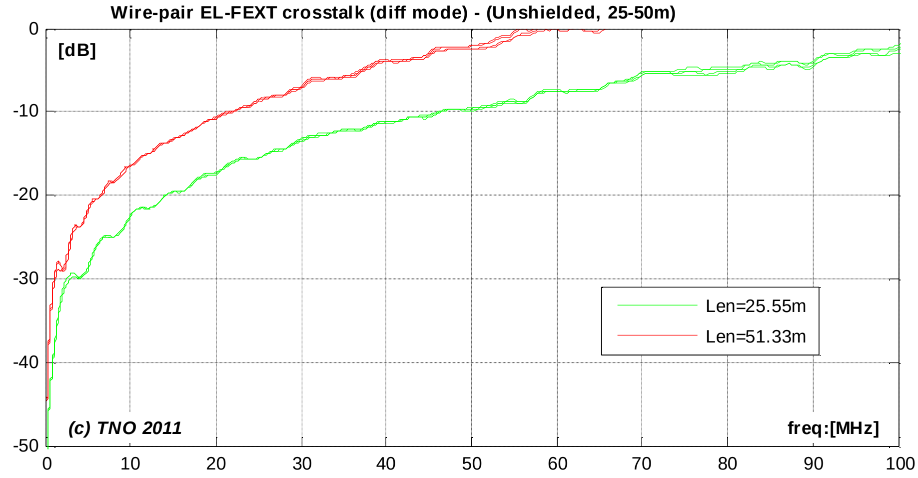
The differential mode NEXT is dependent from the length of the loop, but both are in the same order of magnitude.

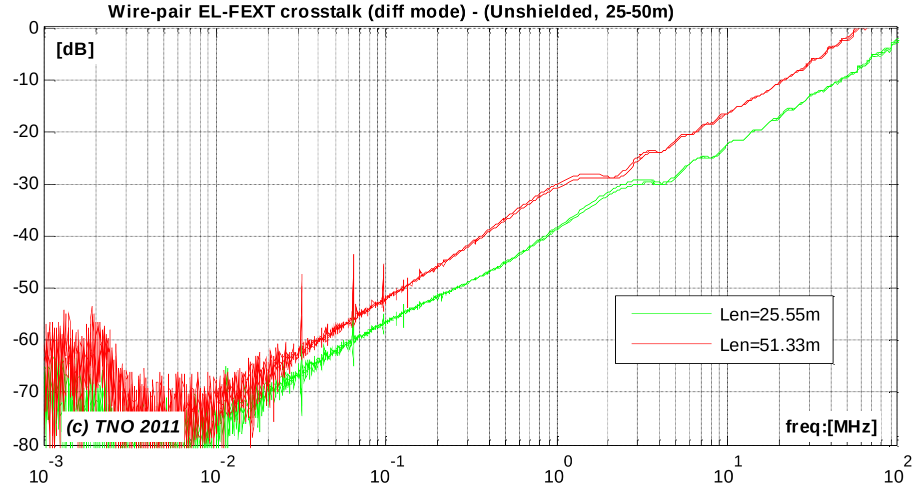


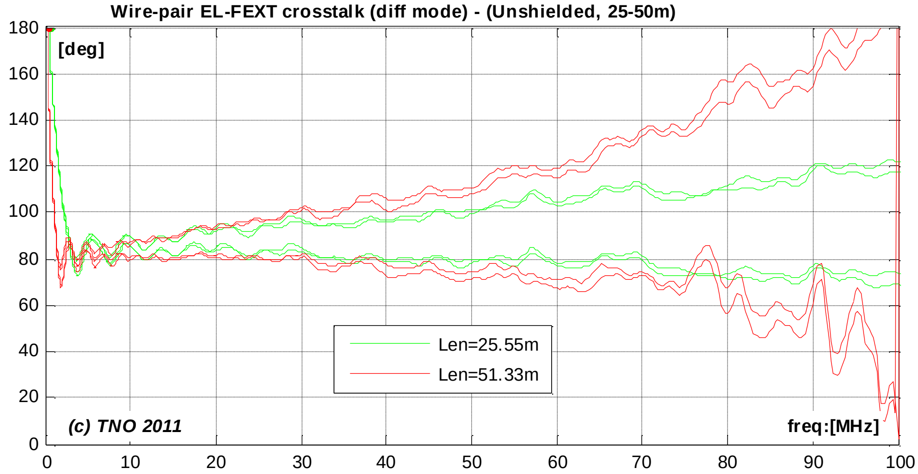
4.5 Far end crosstalk (FEXT and EL-FEXT)

The differential mode FEXT is so high that is almost become deterministic. This demonstrates the low quality of this cabling. FEXT is dependent from the loop length, and therefore we prefer to represent this crosstalk coupling is by means of the EL-FEXT (Equal Level FEXT).
When EL-FEXT is plotted on a log scale then it shows that it approximates a capacitive coupling. The associated phase plot illustrates this as well.





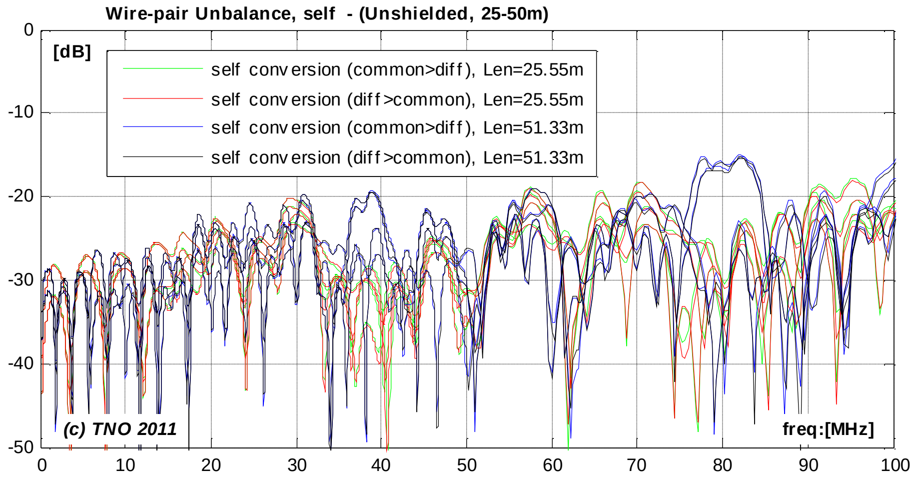




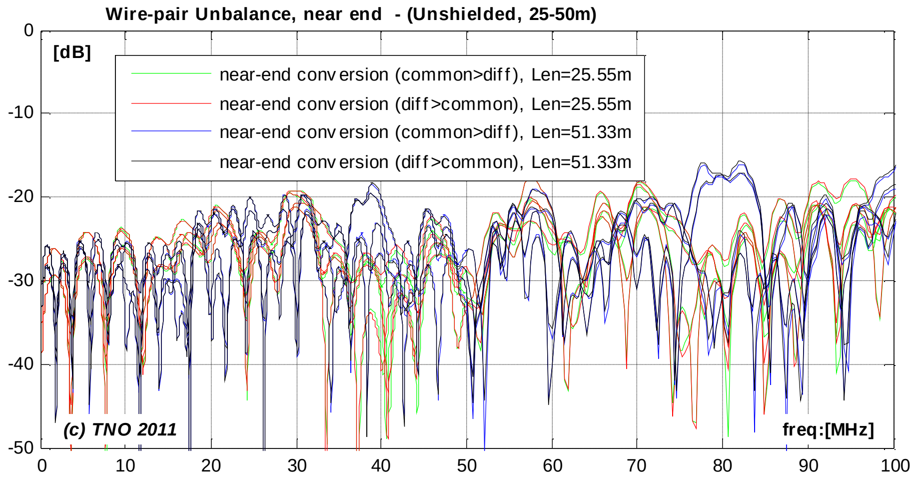
4.6 Unbalance

The unbalance of a cable expresses the conversion from common to differential mode if a common mode signal is injected, or the conversion from differential to common mode if a mode signal is injected. This is a reciprocal process, meaning that both conversion values are to be equal and the figures below illustrate how good this can be observed from the measurements.
The unbalance of all observed wire pairs is in the same order of magnitude, and therefore the different unbalance characteristics are shown for all wire pairs in the same plot.

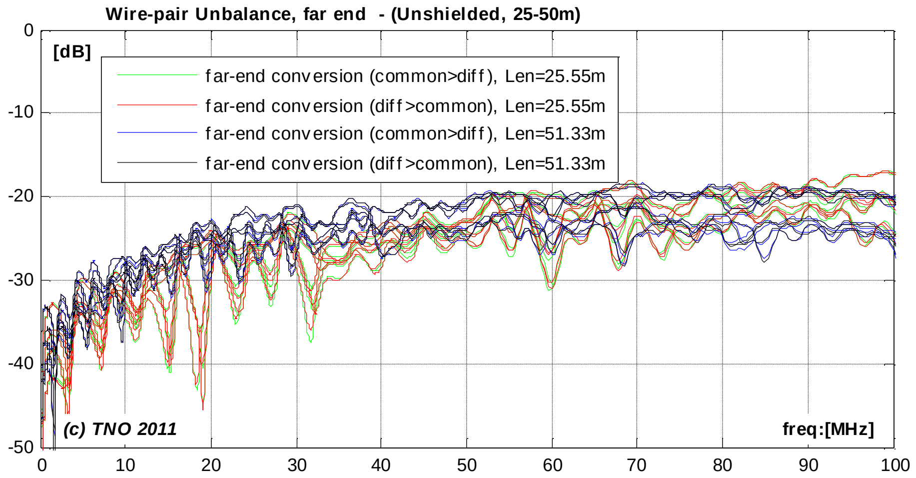
4.6.1 Self mode conversion



4.6.2 Near-end mode conversion



4.6.3 Far-end mode conversion

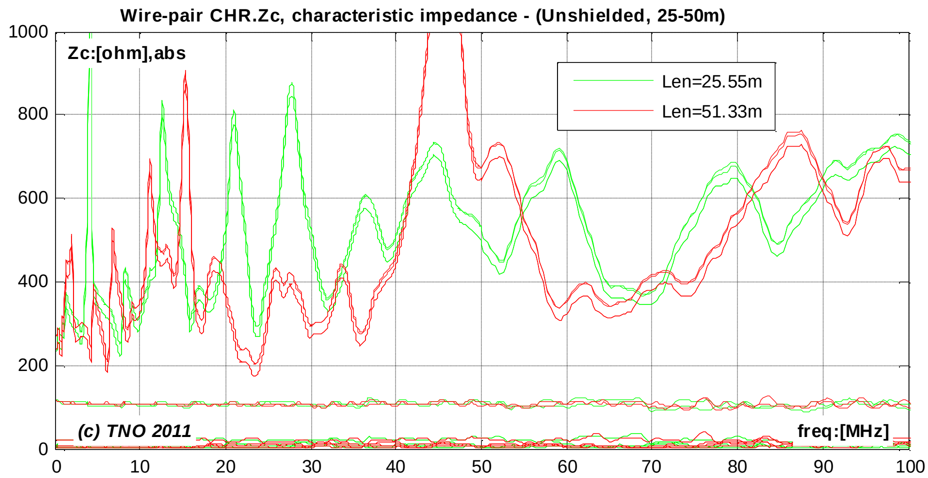


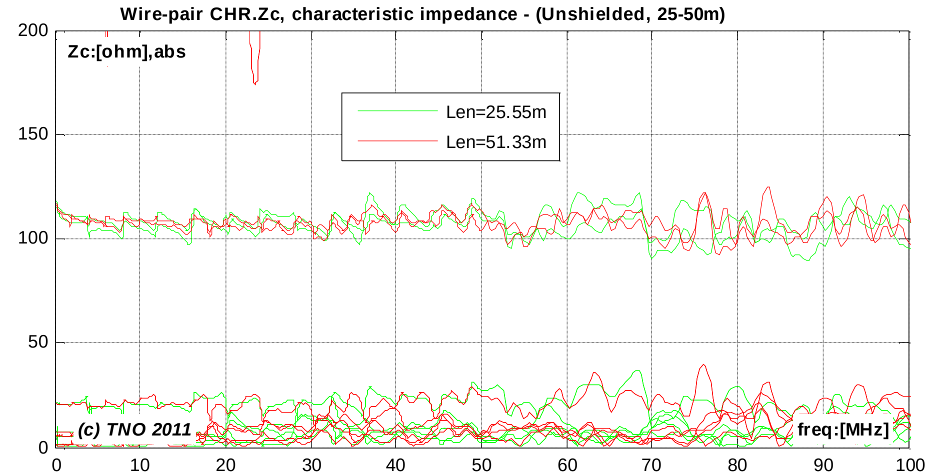
4.7 Characteristic impedance

The (multi port) characteristic impedance is indicative for the (multi port) input impedance of a very long loop. This multiport impedance can be represented by means of a matrix-representation (z-parameters are convenient for matrix calculations) and by means of an equivalent circuit representation (convenient for physical interpretation). Both are shown below.

4.7.1 Matrix parameters (of wire pairs)

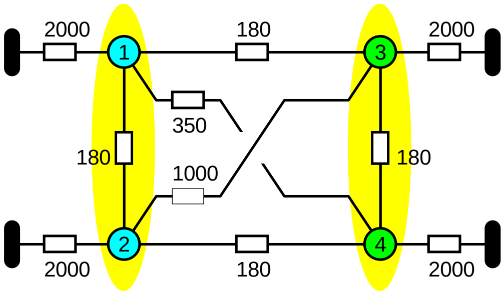
The multi-port matrix parameters for the in-quad wire pairs are a bit different of those for the out-of-quad wire pairs. Both are shown below in different figures. These curves are a combination of the differential mode Z_c, (about 105 ohm) the common mode Z_c (300-1000 ohm) and other coefficients. The common mode curves are highly frequency dependent, probably due to the fact that there was no shielding or return wire used for common signals.

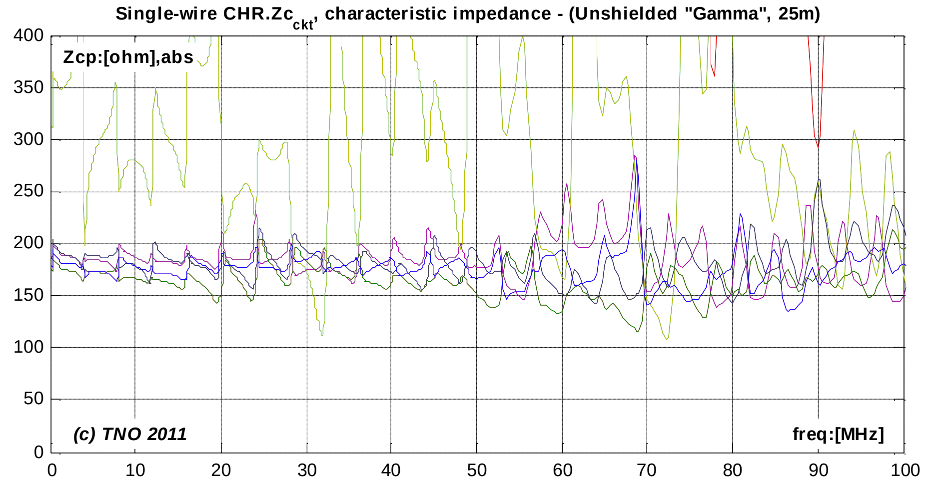


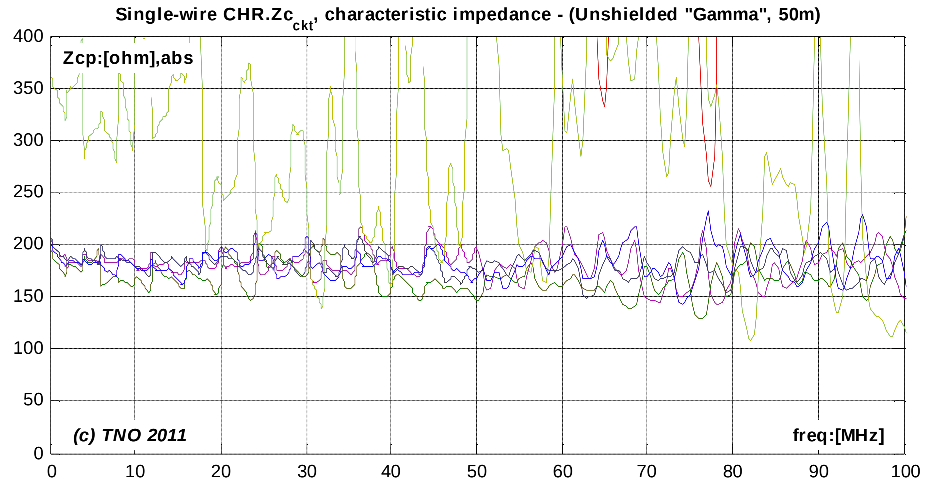


4.7.2 Equivalent circuit parameters (of single wires)

Another way to represent the (multiport) characteristic impedance is by means of an equivalent circuit diagram having the same z-parameters. The extracted impedances between the individual wires for the various wires, and are shown in the figures below. An equivalent circuit that appoximates these impedances is also shown below. It has very high impedances of about 2000 ohm (between wire and "common"), 180 ohm (between twisted wires) and 350-1000 ohm (between cross wires).



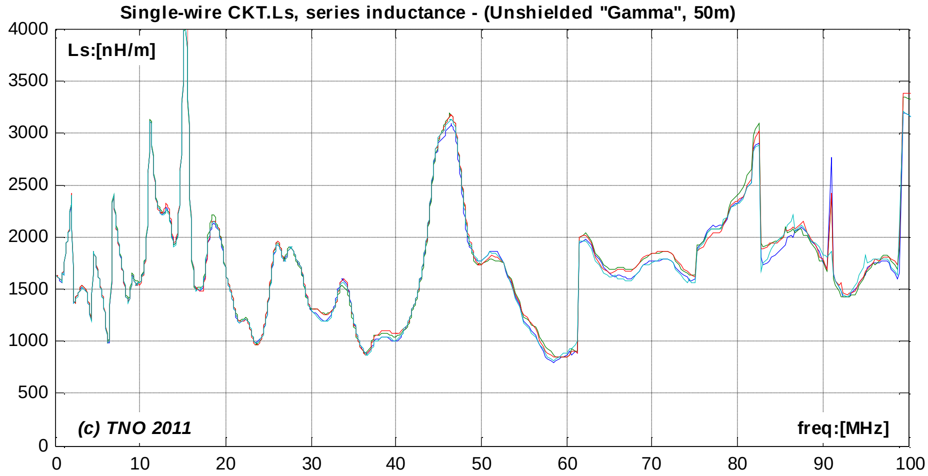




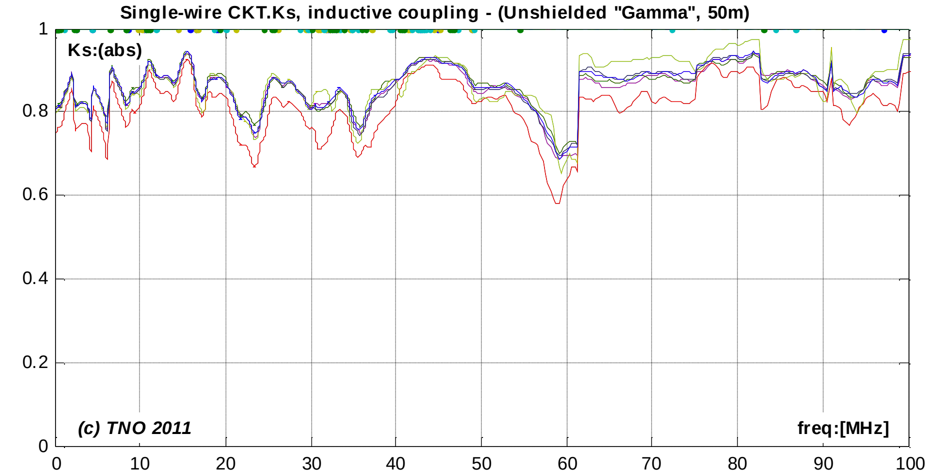
4.8 Primary parameters (single wires)

The extraction of primary (multi port) is a delicate mathematical process, where one solution is to be chosen out of an infinite number of possibilities. Since the full mathematical details of this extraction is out of scope of this deliverable, we restrict ourselves to show the results.
The extracted curves are shown below. The absence of all shielding may be the cause of relatively high serial inductance values and magnetic coupling factors (compared to the shielded cables).

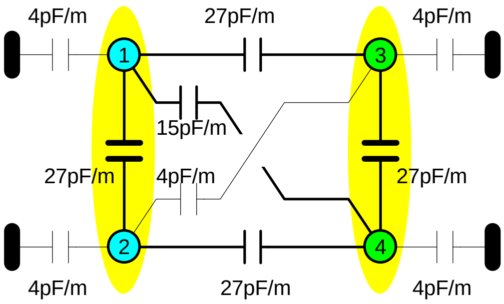
4.8.1 Series inductance of individual wires

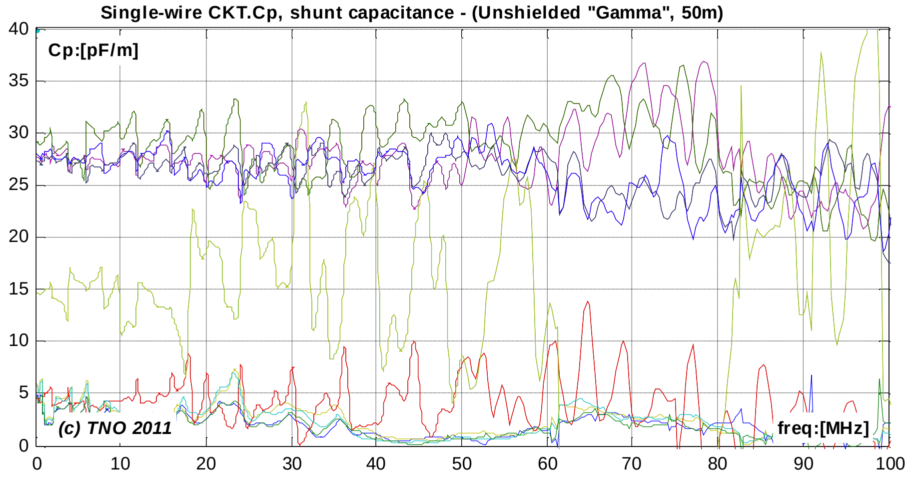


4.8.2 Magnetic coupling between individual wires



4.8.3 Shunt capacitance beween individual wires and/or shielding




Single-wire CKT.Cp, shunt capacitance - (Unshielded "Gamma", 50m)
Cp:[pF/m]
(c) TNO 2011
freq:[MHz]
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100

5 SUMMARY / CONCLUSIONS

We characterized in different kinds of cables in great detail, and all being used in the Netherlands.

- A high quality cable, typically used for interconnecting Gigabit Ethernet networks, is fully capable of transporting signals of hundreds of MHz when it is 200m long. It is probably due to the twist of wire pairs in these cables, which is of such a high quality that the far-end crosstalk is still low enough for this.
- A medium quality cable, typically used within buildings for interconnecting analog telephony , is capable of transporting signals op to 50-100MHz if it is 200m long. Most of the crosstalk is dominated by crosstalk from another wire pair in the same quad, but advance crosstalk cancelation techniques may extend the maximum usable frequency.
- A low quality “telephony’ cable, as found in a consumer shop, is indeed of such a low quality that 50 MHz is usable up to 50m. The lack of any twist of wire pairs, and the lack to preserve a geometry of these wires at any place in the cable is most likely the cause of this.

Although decent performance calculations were not performed, we have not found a fundamental limitation for using that medium quality telephony cable for transporting hundreds of Mb/s over a reasonable loop length.