THE IMPACT OF METAL TRAY SYSTEMS ON THE TRANSMISSION BEHAVIOR OF UNSHIELDED DATA CABLES

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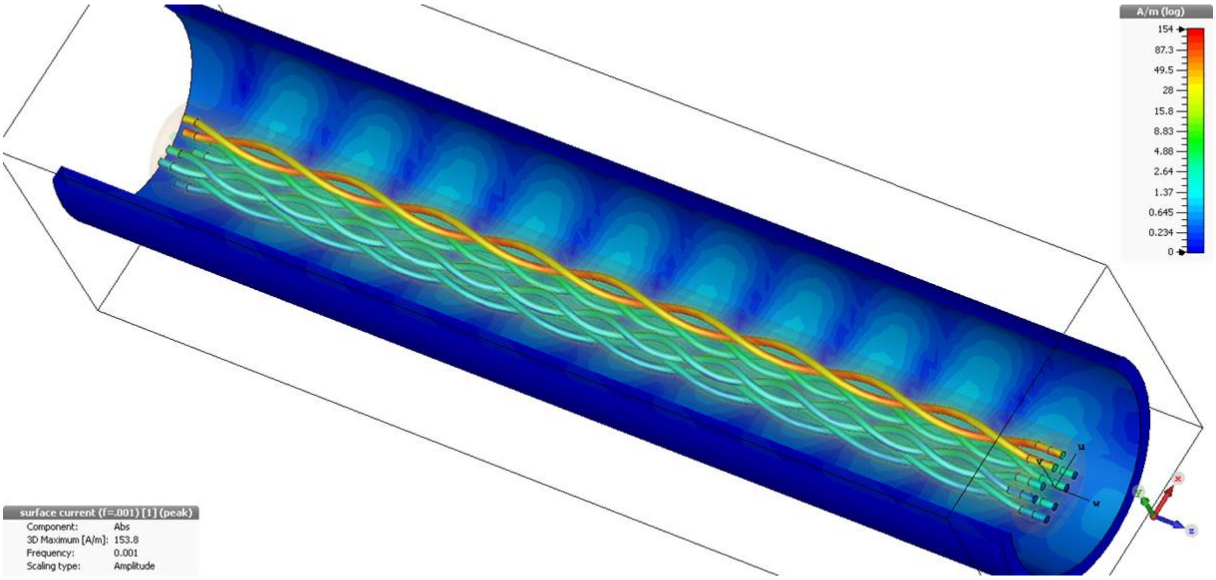
Abstract

In modern local area networks (LAN), the data is almost always transmitted symmetrically through the physical information channel. This means that a two wire line is required to allow the transmission of signals. A typical data cable contains four of these wire lines in order to significantly increase the channel capacity. The simplest form of data cable is realized with just four wire pairs twisted with varying pitches. Shielding around individual pairs or the entire cable can improve the electrical characteristics further. Although the shielded cable has many advantages such as better transmission characteristics, greater bandwidth and a higher immunity to interference, simple unshielded cables are still used in many applications. Shielded cables concentrate the electric and magnetic fields largely within their cross-section, which effectively rules out the influence of the surroundings on the properties of the cable, but for unshielded cables metal conductors outside the cable cross-section also need to be considered. If metallic cable trays are used with unshielded cables, these can affect the capacitive and inductive relations of the cable. This study investigates the extent to which the transmission characteristics of the cable are negatively affected by being placed in a metallic cable tray. Both simulation – with CST MICROWAVE STUDIO® (CST MWS) and CST CABLE STUDIO® (CST CS) – and experiment are used to search for an answer.



Surface currents in the metal pipe, arising from the unshielded cable

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1. Foreword

This topic arose as a question at the “Technical Exchange Meeting” at the newly-opened factory in Taicang, China in October 2014. The research project was initiated by Mr. Zeng Songming, the leader of the on-site development department, and was carried out as a joint project within the R&D department at DATWYLER in co-operation with the company CST. Alongside the original goal of answering the question, this work is also intended to demonstrate the potential of simulation software for answering technical questions of this sort in the field of high-frequency engineering. We thank all participants, especially Mr. Franz Hirtenfelder (CST), who performed all these simulations.

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2. Introduction

Ethernet has established itself so thoroughly as the network technology for LAN that today the two are effectively synonymous. Historically, this development was especially encouraged by the worldwide publication of the first IEEE-defined standard as an international norm (ISO/DIS 8802/3) in 1985. Its popularity was increased further by the fact that instead of coaxial cables it used twisted pairs, which were already familiar from their use in telephone networks (see [1]).

The rising demands placed on LAN by ever-increasing data rates meant that these cables were constantly developed in order to improve their transmission characteristics. This evolution led from the original simple twisted pair through unshielded cables to the modern shielded data cable, which offers high performance due to its interference immunity and transmission characteristics (see [2; page 28ff]).

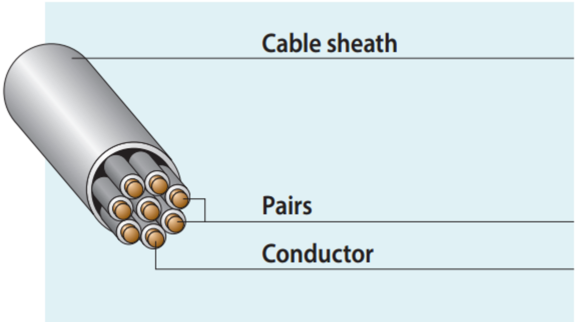

Fig. 1: unshielded data cable (U/UTP)

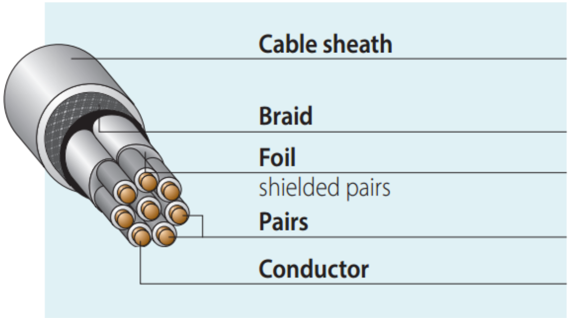

Fig. 2: shielded data cable (S/FTP)

Shielded cables are the way of the future, and can easily fulfill the requirements of the 10GBase-T technology according to IEEE 802.3an, which allows data rates of up to 10 Gbit/s. Furthermore, there is currently no physical transmission channel technology defined which offers higher data rates based on four symmetric wire lines. Shielded data cables offer that potential.

Due to the historical roots and the fact that data networks are not always future-proofed or optimized for maximum possible data rates, unshielded cable systems are still very commonly used for some applications in many countries.

Fig. 3: unshielded data cable CU 662

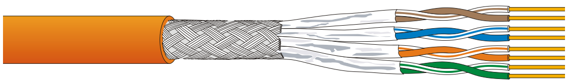

Fig. 4: shielded data cable CU 7150

With the use of unshielded cables and the corresponding higher sensitivity of the physical transmission channel to the electrical characteristics of the surroundings, a reasonable question arises: how much could this actually interfere with data transfer? The following study therefore focuses on the possible influence of the metal cable trays on the transmission characteristics of an unshielded cable.

3. Methods und Goals

2.1. General

The goal of this study is to show whether the metal cable conduit can influence the electrical characteristics of unshielded cables to such an extent that it could interfere with data transmission at data rates of 1 Gbit/s. The electrical requirements for the cable, which correspond to those needed at minimum for 1000Base-T (IEEE 802.3ab), are those of Class D (see [3; Table F.1]) – specifically for single components corresponding to Category 5 (see [3, page 51]). Many data networks use higher-performance Category 6 cables with electrical requirements in the baseband specified up to a frequency of 250 MHz.

2.2. Experimental procedure

At the outset, objective criteria are required that ensure that a data rate of 1 Gbit/s according to IEEE 802.3ab can be realised for the transmission channel under study. Because the measurement and simulation of data rate and bit error rate in the time domain were expensive and could not be carried out, the characterization was instead performed in the frequency domain. The corresponding cable standards contain the required specifications for the physical transmission channel in the frequency domain, and define the transmission characteristics required in this regard for the cable (see [4]). The reference length for this cable is 100 m, which is impractical for experimental study. Instead, shorter lengths of the unshielded Category 6 “DATWYLER CU 662” data cable (see [2; page 76f]) were used to carry out the measurements shown in Table 1.

<table>
<tr><th colspan="4">Measurements</th></tr>
<tr><td colspan="2" rowspan="2">TEST OBJECT
DATWYLER CU 662</td><td colspan="2">Copper pipe
Ø 10 mm</td></tr>
<tr><td>with</td><td>without</td></tr>
<tr><td rowspan="2">Length [m]</td><td>2.5</td><td>✓</td><td>✓</td></tr>
<tr><td>10</td><td></td><td>✓</td></tr>
</table>

Table 1: Measurements of transmission characteristics in the test object

For a cable length of 2.5 meters, a simple metal cable conduit was constructed in the laboratory using a copper pipe. Together, the three measurements in Table 1 form the cornerstones of the study. The cable model obtained from the available simulation software CST MWS and CST CS can be optimized by adjusting the geometrical cable dimensions and material properties of the model to accurately approximate the transmission characteristics of the real cable. Verifying the cable model with simulation in this way gives high confidence in the results.

Fig. 5: Data cable in a pipe – length 2.5 m

Fig. 6: Data cable – length 2.5 m

Starting with the verified cable model obtained in this way, all of the other changing conditions regarding the length, the diameter of the copper pipe etc. can be easily calculated by interpolation and extrapolation of simulated results. This allows not only the necessary verification of the requirements of the standard, which are based on a 100 m cable length, but also the calculation of the effect on the transmission characteristics of the metal pipe for a greater range of variations.

2.3. Measurements and “Model Curves”

The number of measurements required means that it’s not practical to verify the transmission characteristics of the cable model for every parameter of every twisted pair individually. Instead it makes more sense to initially use measurement to define all transmission characteristics and use this simplification – so called “Model Curves” – to compare them with the simulated cable model results. This means that the exact details of its behavior are lost, but the tendencies are easier to recognize. For each of the three measured cases, the envelopes of curves for the different twisted pairs for the individual parameters are defined using step functions. Table 2 shows the step frequency points with some selected parameters as an example:

Step-Frequency f [MHz]		**1**	**4**	**10**	**100**	**250 500**
Return Loss [dB]			23	27	25	21
Impedance Z [Ω]	**top**		115	108	112	115
	bottom		96	96	94	94
NEXT [dB]		83	81	61	52	46
TCTL[dB]		54	50	44	34	34

Table 2: Envelopes of the transfer parameters from a 10 m length of CU 662

Only the attenuation is considered differently. The attenuation of the measurements is approximated according to its theoretical formula (see [5: D20, D24]), which combines a linear frequency component added to one that is proportional to the square root of the frequency. The first term of the attenuation function represents the dielectric losses, and the second term represents the Ohmic conduction losses. Table 3 shows the attenuation parameters for the three measured cases.

Attenuation CU 662: a f[MHz] + b √(f[MHz])			
Length [m]	**Pipe**	**a**	**b**
10	no	0.00090	0.1690
2.5	no	0.00048	0.0398
2.5	yes	0.00043	0.0398

Table 3: Parameters for the attenuation formula

For a better illustration, the envelopes of the “model curves” - based on measured data - for the parameters listed in Table 2 are shown in Figures 7 to 10, and the envelope for the attenuation for an approximate length of 10 meters is shown in Figure 11.

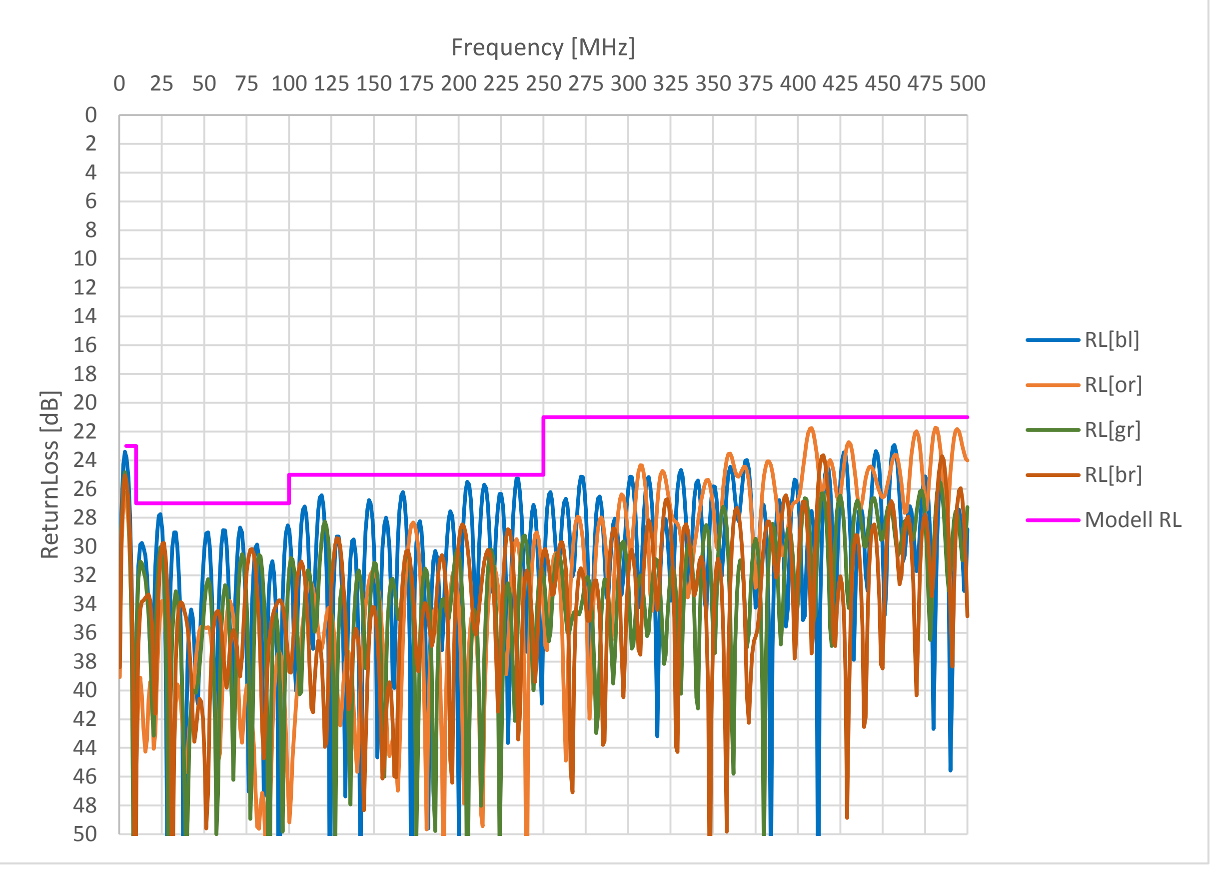

Fig. 7: Measurements of the return loss of CU 662/ length 10m with model curve

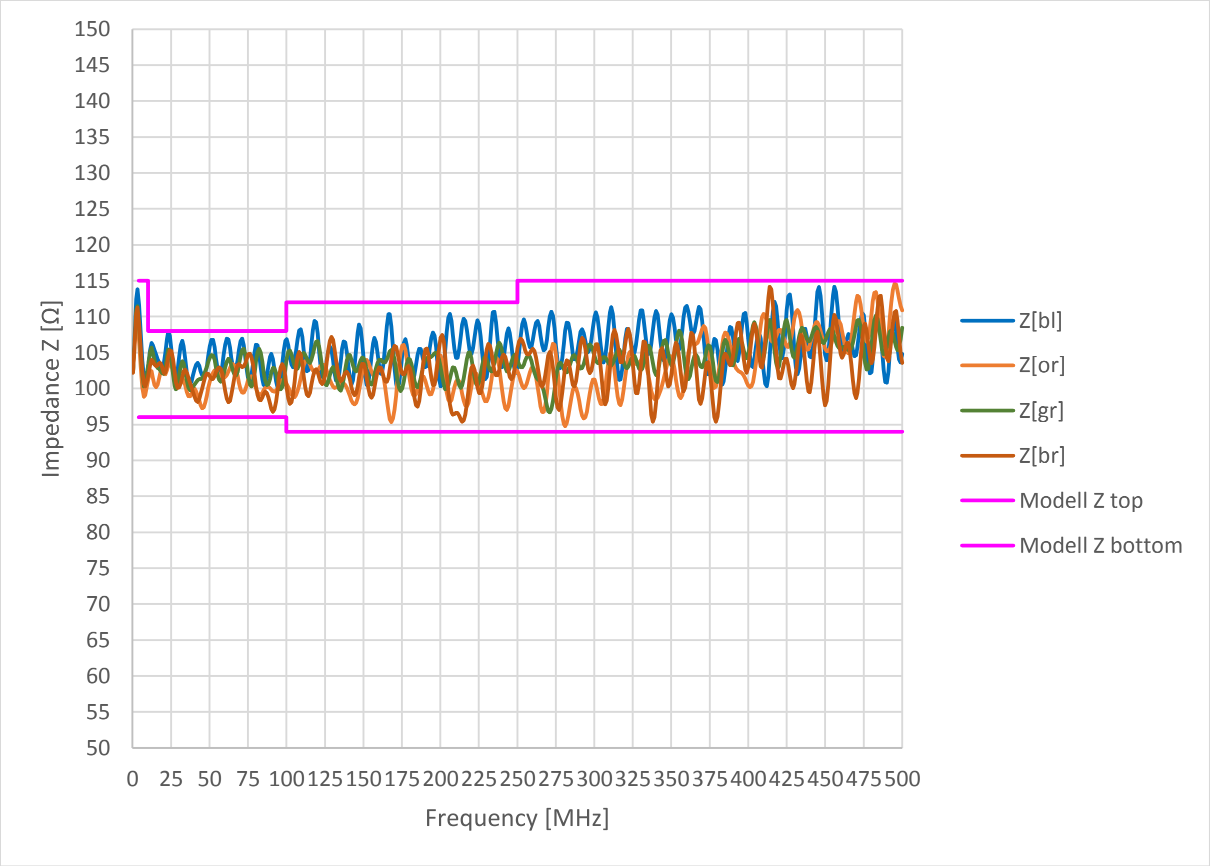

Fig. 8: Measurements of the impedance of CU 662/ length 10m with model curve

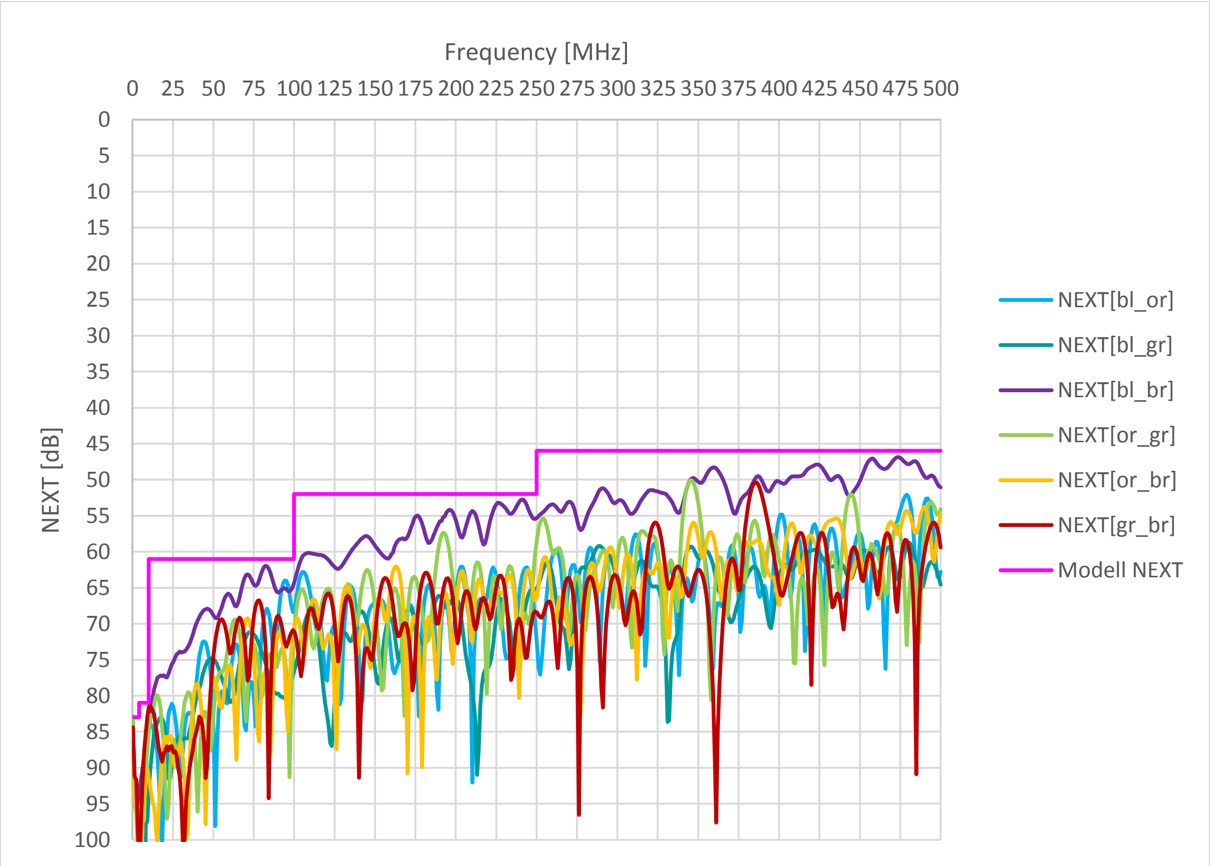

Fig. 9: Measurements of the crosstalk (NEXT) of CU 662/ length 10m with model curve

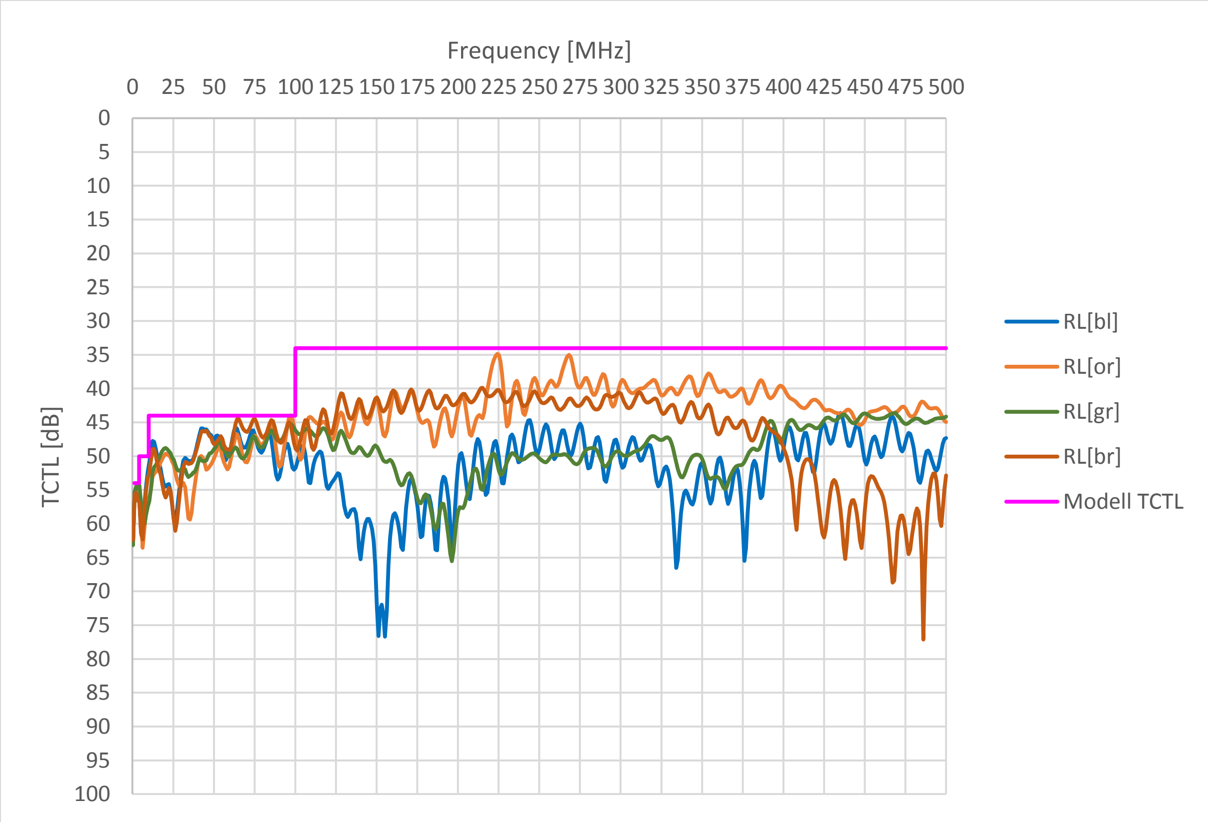

Fig. 10: Measurements of the transverse converse transfer loss (TCTL) of CU 662/length 10m with model curve

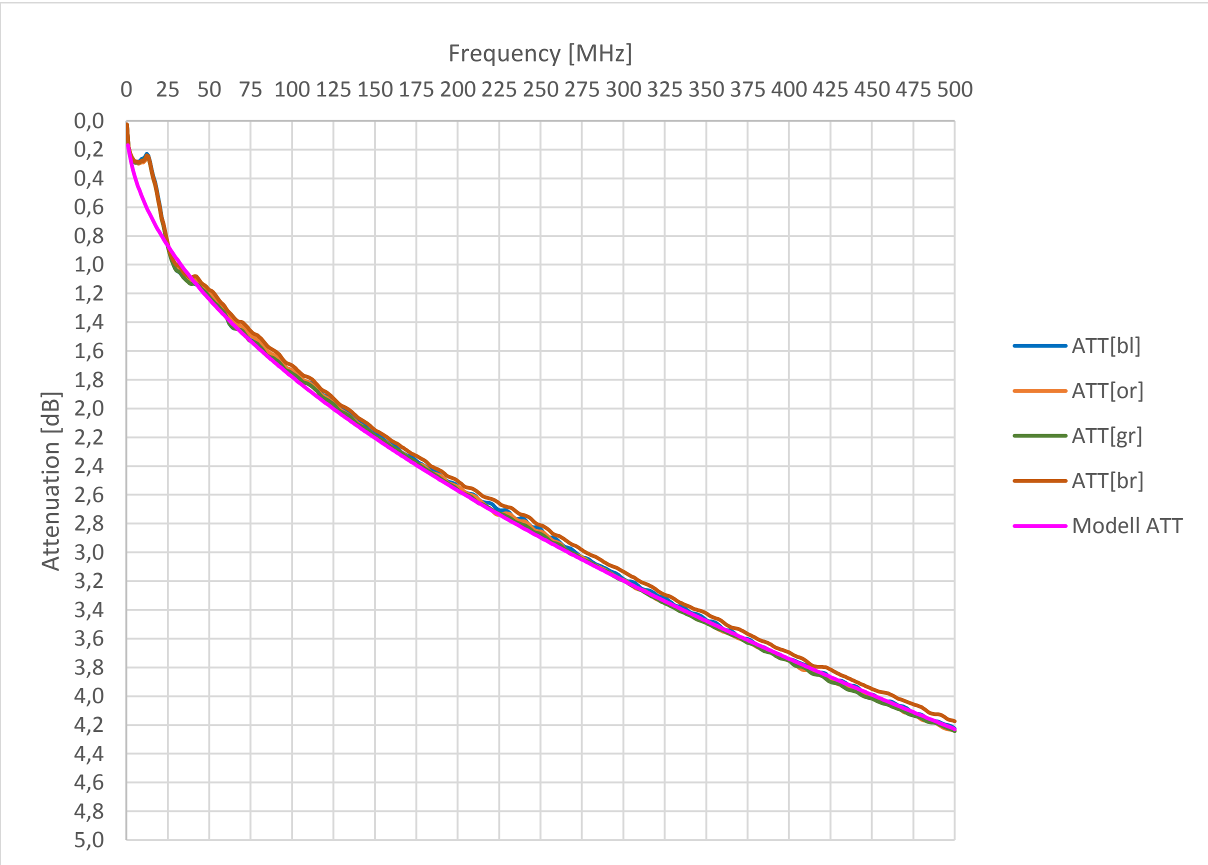

Fig. 11: Measurements of the attenuation of CU 662/length 10m with approximated model curve

2.4. Cable model und verification

The simulation software tools CST MWS and CST CS were used to develop a cable model for the CU 662 data cable. The model was verified by the three experimental configurations (see Table 1) using the model curves based on the measurements. The goal is a good agreement between the simulated transmission curves of the cable model and the model curves – based on measurements - for each of the three configurations. This ensures that the CU 662 cable is realistically represented by the cable model.

Construction of CU 662								
pair	Color	Ø Cu [mm]	Ø Wire [mm]	Material	Pair twist		Cable twist	
					Twist direction	Pitch [mm]	Twist direction	Pitch [mm]
I	white	0.55	1.03	PE	left	9.06	left	70
	blue	0.55	1.03	PE				
II	white	0.55	0.99	PE	left	12.60		
	orange	0.55	0.99	PE				
III	white	0.55	1.03	PE	left	9.65		
	green	0.55	1.03	PE				
IV	white	0.55	0.99	PE	left	13.95		
	brown	0.55	0.99	PE				

Table 4: Construction data for the CU 662 cable

On the basis of the construction data, the most important parameters of which are listed in Table 4, a cable model was constructed in CST CS, hierarchically laid out from the individual wires to the cable sheath.

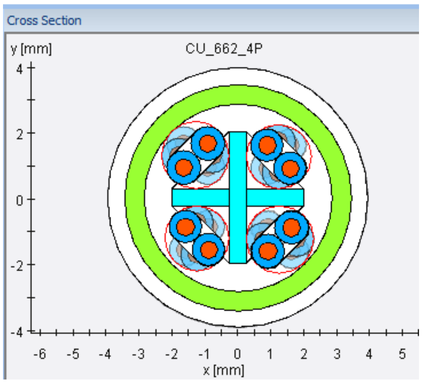

Fig. 12: Model of cable CU 662

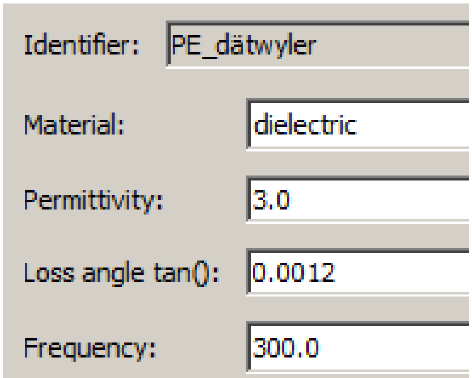

Fig. 13: Material specification in CST CS

Figure 12 shows this cable model with the key elements of the simulated cable CU 662: the four twisted pairs, the cross that separates them and the cable sheath. The initial model assumes that the cable fits the specification perfectly and that the production process is ideal and/or error-free. The dielectric properties of the wire sheaths in the model are shown in Figure 13.

The circuitry of the cable model is represented schematically in Figure 14. The converters which are attached both ends of the cable enable direct access to the common mode (C) and the differential mode (D) on two of the pairs. To replicate the measurement process with the network analyzer, the common mode is terminated with 25 Ω and the differential mode with 100 Ω. The wires from the other pairs, which are not required, are terminated with 50 Ω.

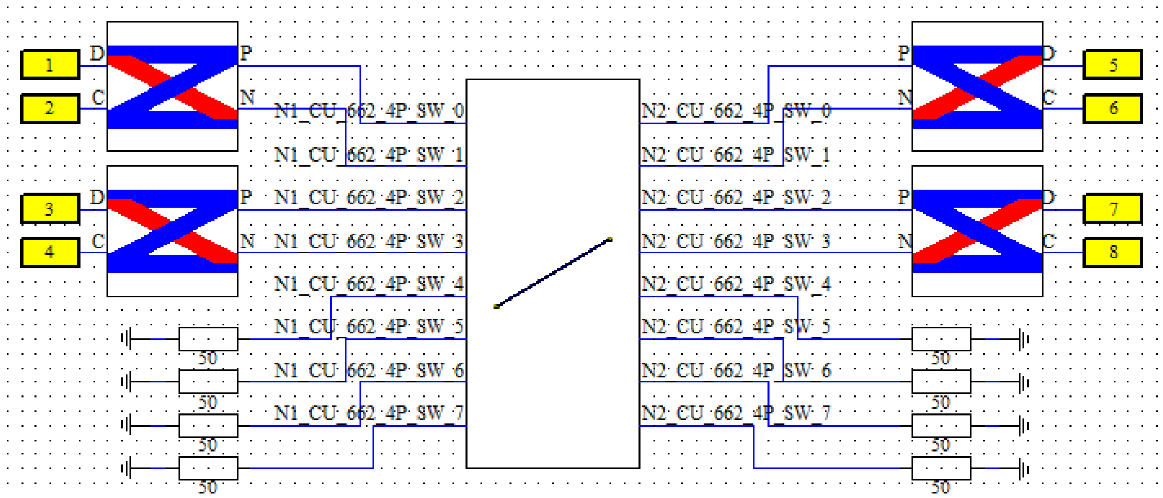

Fig. 14: Typical circuitry for the cable model, with converters.

Obtaining a satisfactory agreement of the attenuation behavior between measurement and simulation is a simple matter of adjusting the dissipation factor ("Loss angle tan()" in Figure 13), which was not sufficiently well known for high frequencies. The simulation also offers the ability to verify the material properties. Figure 15 shows the simulated attenuation curves of the cable models and the model curves for attenuation derived from measurement for the three experimental configurations.

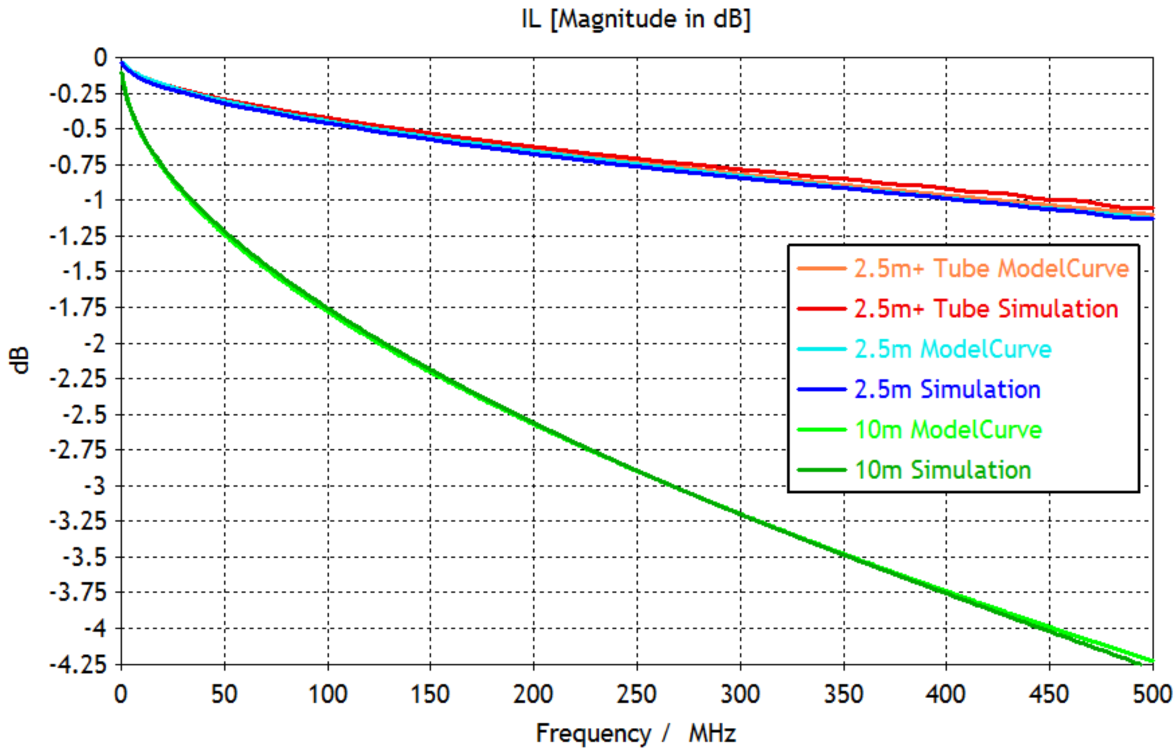

Fig. 15: Insertion loss of cable model simulations and model curves for CU 662, AP[blue]

This first simple cable model offered good agreement with regards to attenuation, but it was not possible to approximate with the desired accuracy all the transmission parameters that correspond to the symmetry of the cable (TCL, TCTL, imbalance).

Since the symmetry of these ideal cable models with respect to magnitude and phase was too idealised, a mechanical asymmetry was postulated. The wire pairs were defined with an eccentric twist, which led to a better agreement between the transmission parameters of the real cable and the cable model.

CST CS allows this degree of freedom to be modeled (Figure 16). Interestingly, displacing the twist axis by just 5 µm to 8 µm was sufficient to give a satisfactory agreement between simulation and measurement. This in turn means that the simulation offers additional useful information about the accuracy of the production process.

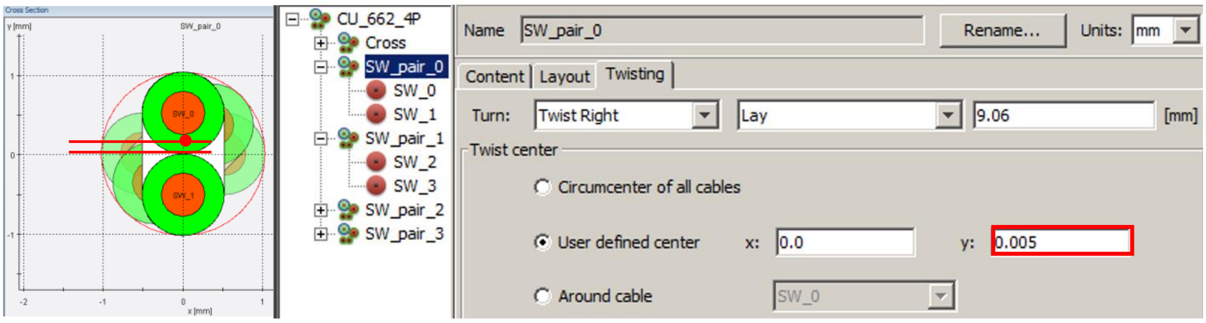

Fig. 16: Modeling the CU 662 with eccentric twist

The TCL and TCTL parameters are a measure of the common mode rejection ratio of the reflected and transmitted signals. These correspond to the S-parameters S2,1 and S6,1 of the blue twisted pair in Figure 14. The TCTL is shown in Figure 17. When eccentric twisting is included, the simulated curves agree satisfactorily with the measurement based model curves.

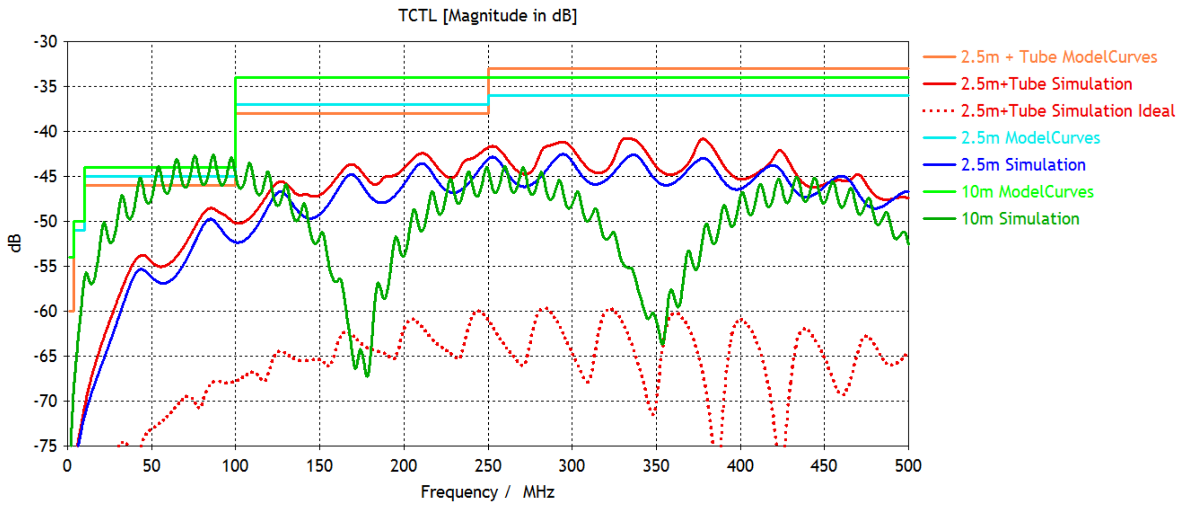

Fig. 17: TCTL with eccentric twist

For the imbalance parameter, the schematic of the model needs to be slightly changed by removing the converter at the far end, as shown in Figure 18. Both wires of the twisted pair are instead directly connected to 50 Ω ports (5; 6). An ideal 180 degree phase shifter is added before one of the ports to eliminate the inherent phase difference of the differential mode. In this setup the imbalance is the ratio of the S-parameters S5,1 and S6,1.

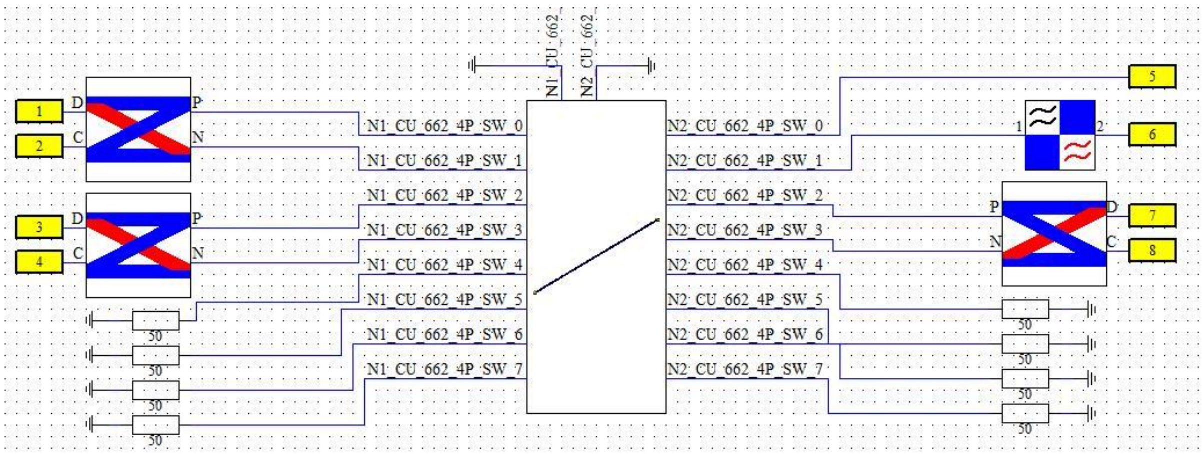

Fig. 18: Schematic circuit for modeling the imbalance

Figures 19 and 20 represent the magnitude and phase of the imbalance for the eccentric twist model parameters. With the eccentric twisting, there is a satisfactory agreement between the model and the real cable. For an ideal perfectly symmetrical cable, both the magnitude and the phase of imbalance across the entire frequency range are effectively zero (dotted lines).

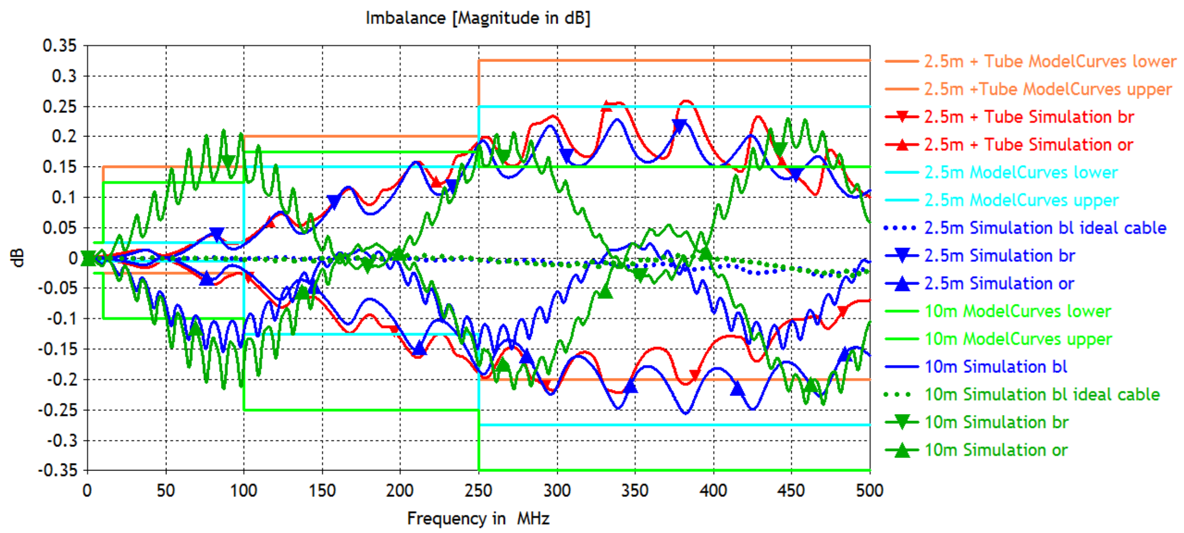

Fig. 19: Magnitude of imbalance

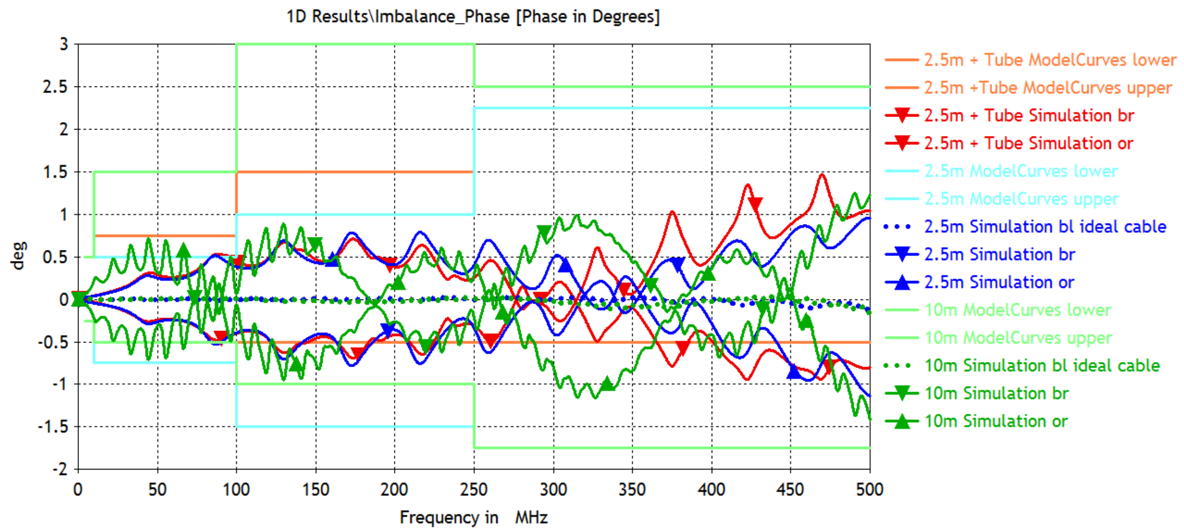

Fig. 20: Phase of imbalance

Despite these refinements, a further large discrepancy between the model and the real cable is seen in the near-end crosstalk (NEXT), as shown in Figure 21.

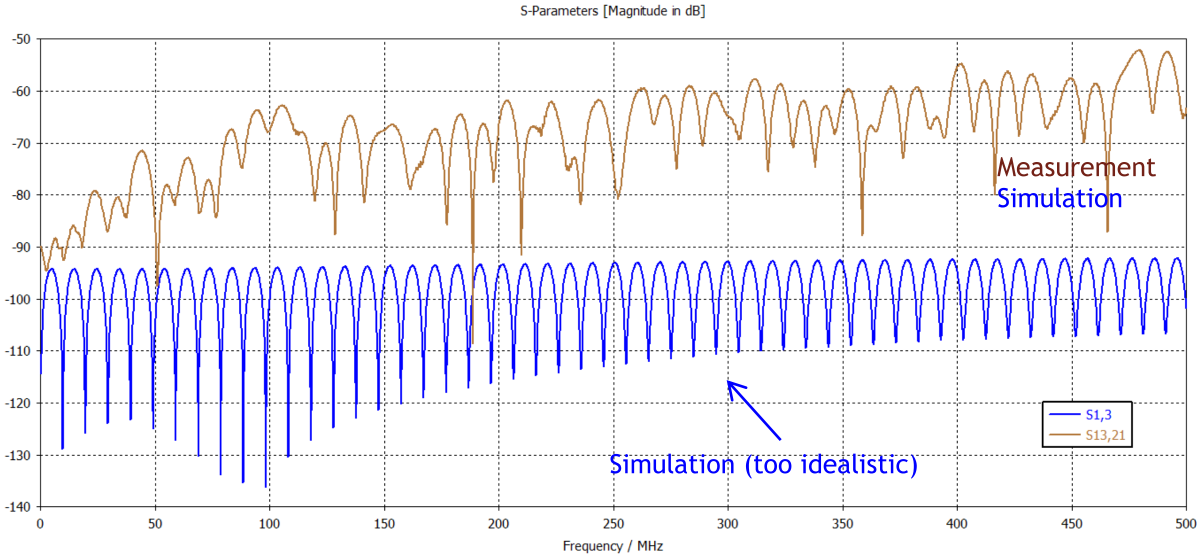

Fig. 21: NEXT [blue-orange] of CU 662 (length 10 m)

Attempts to adjust the cable model itself – for example, by narrowing the separator or bringing the pairs closer – didn't improve the agreement. Since the crosstalk can be strongly influenced close to the reference plane and changing the cable itself was not successful, the connectors themselves were examined in more detail.

The influence of the measurement connector on the crosstalk was investigated with CST MWS. A photograph of the connector and the 3D simulation model, constructed from the data sheet specification directly in the CST MWS design environment, are shown in Figure 22.

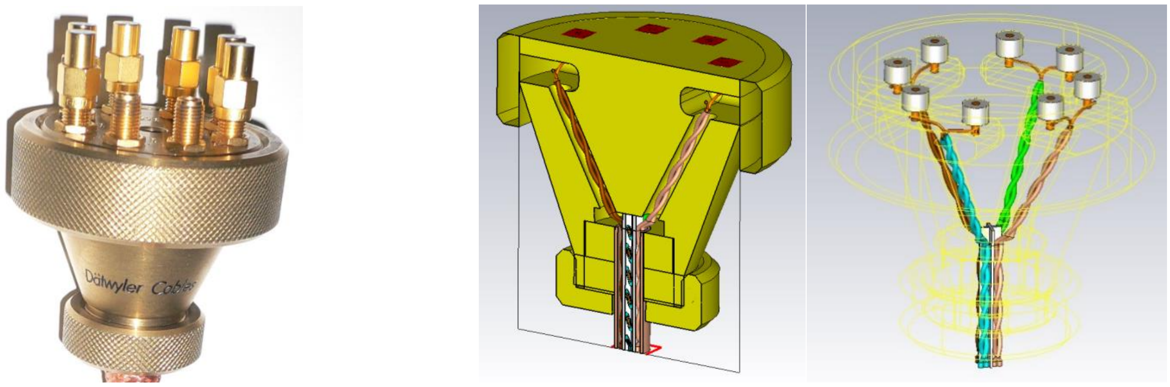

Fig. 22: Real cable measurement connector and mechanical model in CST MWS

The complete set of scattering parameters of the simulated measurement adapter were extracted, using the schematic circuit model shown in Figure 23, with attached mode converters to calculate the differential and common S-parameters.

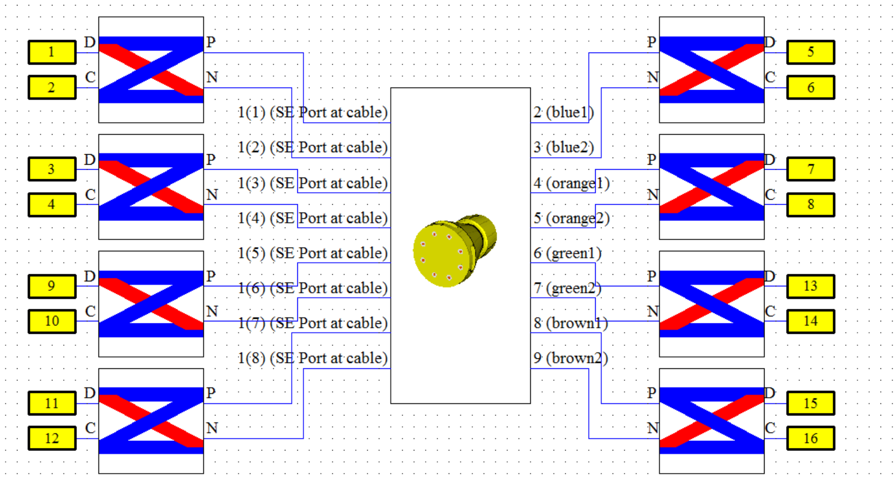

Fig. 23: Schematic circuit of the cable measurement connector in CST MWS with mode converters.

Some important transmission characteristics of the connector are shown in Figure 24. The near-end crosstalk (NEXT) between blue and orange pairs corresponds to S1,3 (in green), which shows that the isolation between twisted pairs at 500 MHz is worse than 60 dB.

The simulation confirms the hypothesis, formerly not taken seriously, that the connector itself significantly affects and limits the measurement of the crosstalk. This presents a paradox: it does not seem plausible that despite the separation of the twisted pairs in the connector, the crosstalk attenuation is less than in the cable itself. This is true of both unshielded and X/UTP cables.

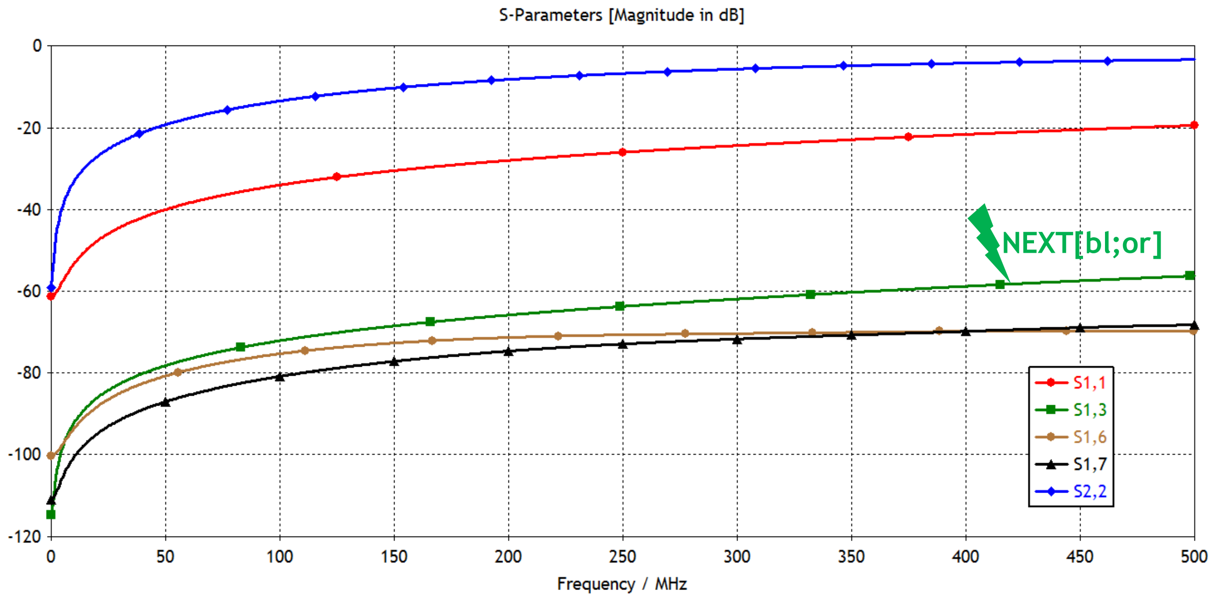

Fig. 24: Transmission characteristics of the separately simulated connectors.

A simulation of the cable taking the connectors into account shows however that including the S-Parameters of the 3D measurement adapter into the simulation (Figure 25) then offers a much better agreement between measurement and simulation (Figure 26).

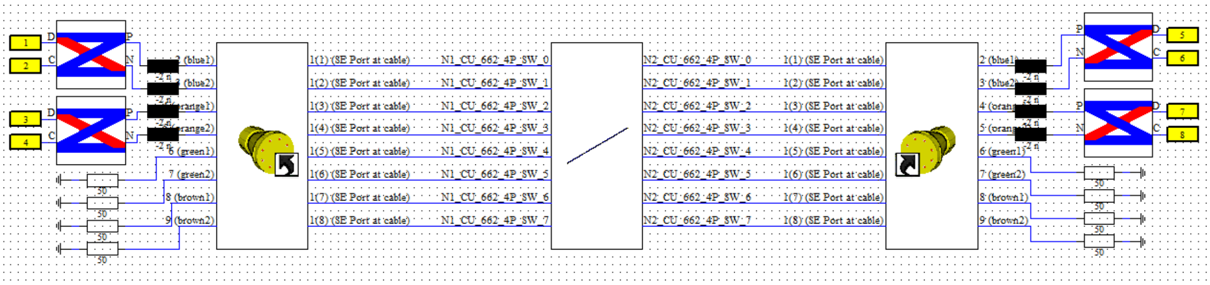

Fig. 25: Schematic construction with 3D connector models.

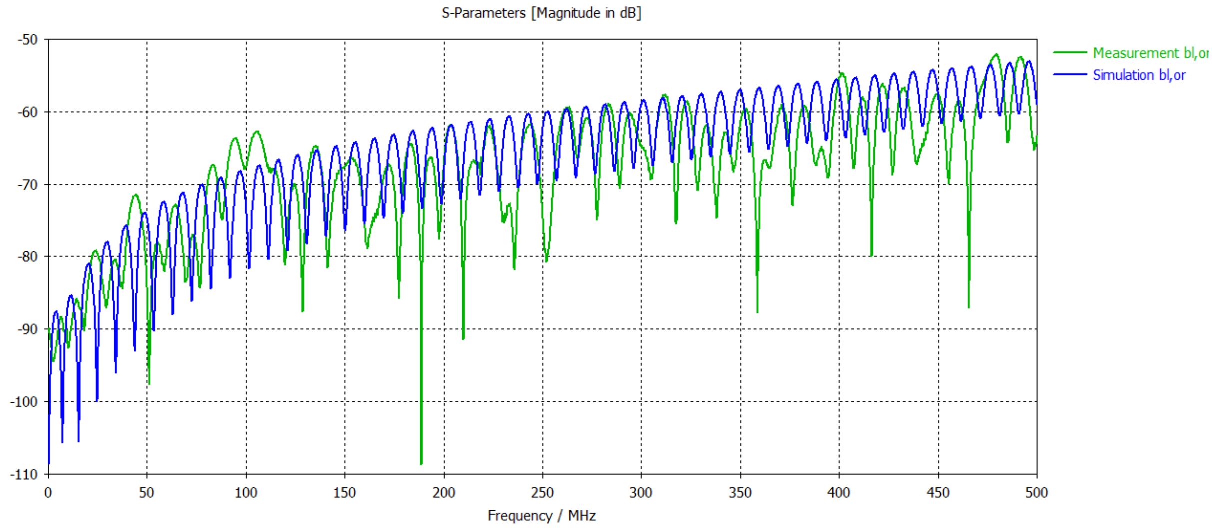

Fig. 26: NEXT (between blue and orange) of the cable model with the connector compared to the measurements.

Since the connector has a significant influence on the measured results, the cable model is now implemented with the 3D connector models as shown in Figure 25. The results from the connector calculation can then be transferred back into the measurements in order to calculate the behavior of the cable itself. This is important when calculating the real behavior of a cable or deciding whether a cable meets the standard requirements.

Figures 27-30 show the parameters NEXT, FEXT, return loss and impedance calculated from the cable model, compared to the corresponding model curves from the measurement.

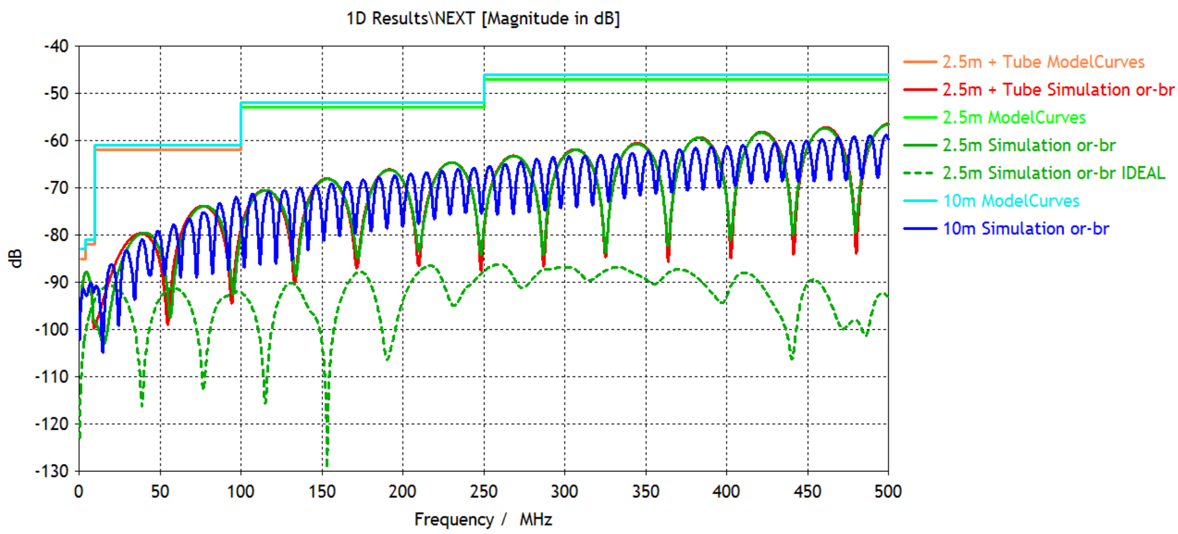

Fig. 27: NEXT[orange-brown] (the dotted line is the cable itself without the adaptor)

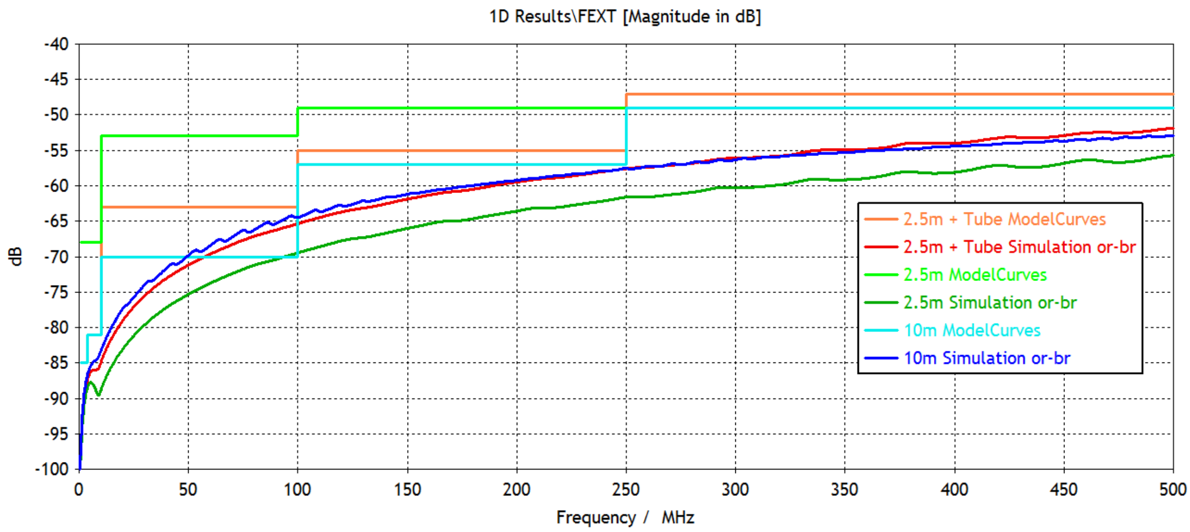

Fig. 28: FEXT (orange-brown)

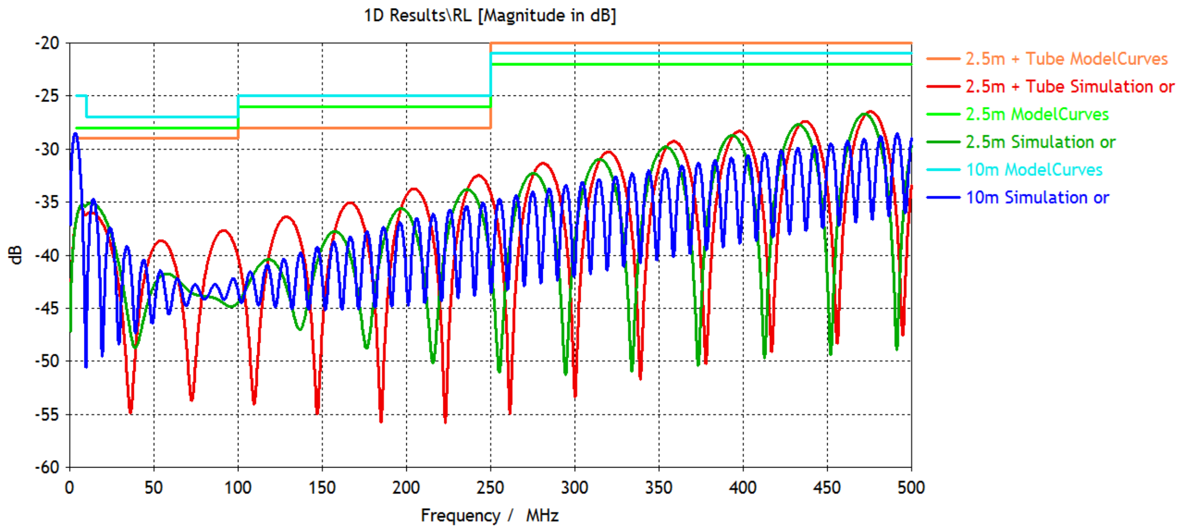

Fig. 29: Return loss for the orange pair

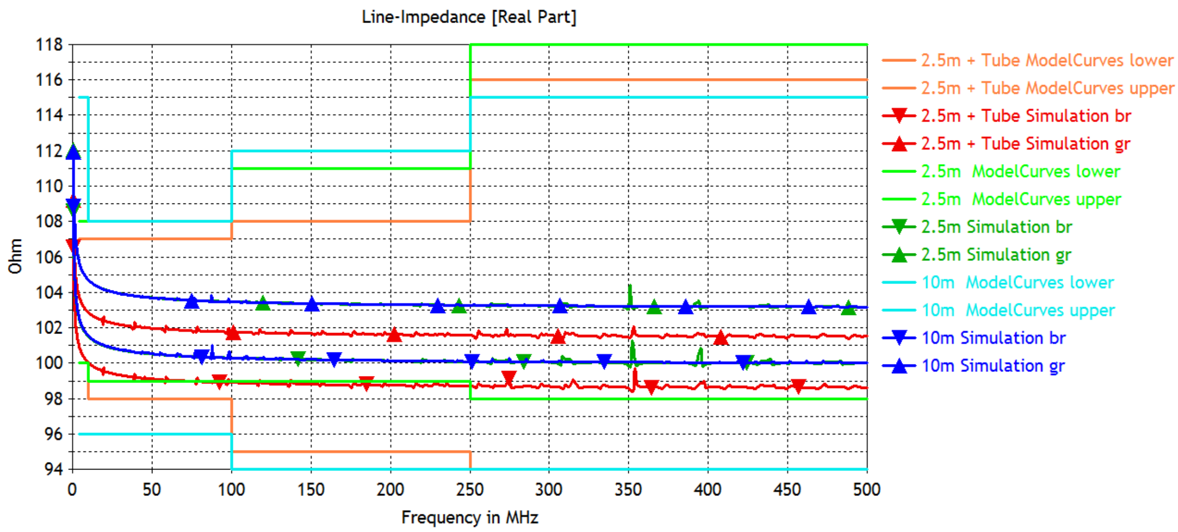

Fig. 30: Impedance for the green and brown pairs.

The difference in line impedances between the green and brown pairs in the cable model in Figure 30 (blue curves) results from the varying thickness of the insulation (see Table 4) and is derived from the varying separation of the copper wires in the twisted pairs. The resulting effective capacitance of both pairs is increased due to the copper pipe, which reduces the corresponding impedance (red curves).

Table 5 collects the most important parameters of the developed and verified cable models for the DATWYLER CU 662 cable.

Name	Expression	Description
coating_di	= 5.7	cable coating inner diameter in mm
coating_thickness	= 0.6	cable coating thickness in mm
excentric_bl_gr	= 5e-3	wire-pair excentric offset in mm
excentric_or_br	= 8e-3	wire-pair excentric offset in mm
Material_Copper	= 5.6e7	conductivity of copper in S/m
Material_cross_eps	= 2.29	Separation Cross dielectric constant
Material_cross_tand	= 4.8e-4	Separation Cross tan delta @ 100 MHz
Material_FRNC_eps	= 4.11	Dielectric constant for FRNC
Material_FRNC_tand	= 4.74e-3	loss angle for FRNC @ 100 MHz
Material_PE_eps	= 3	Dielectric constant for PE
Material_PE_tand	= 1.2e-3	loss angle for PE @ 300 MHz
thickness_bl_gr	= 0.24	Isolation thickness of PE for blue and green in mm
thickness_or_br	= 0.22	Isolation thickness of PE for orange and brown in mm
twist_bl	= 9.06	twist rate of pair blue in mm
twist_br	= 13.65	twist rate of pair brown in mm
twist_cable	= 70	twist rate of complete cable in mm
twist_gr	= 9.65	twist rate of pair green in mm
twist_or	= 12.6	twist rate of pair orange in mm
wire_diameter	= 0.55	single wire diameter in mm
Zc	= 25	Common Mode Impedance in Ohm
Zd	= 100	Differential Mode Impedance in Ohm

Table 5: Model parameters of the cable model in CST CS for the DATWYLER CU 662 cable.

2.5. Cable model and standards conformity

The simulation software tools CST CS and CST MWS were used to develop a model of the CU 662 cable. The model was optimized paying special attention to the transmission parameters of imbalance and crosstalk, and verified with a network analyzer for the three test cases. The accuracy of the model was consider sufficient to be used to be derive the essential criteria that decide whether, and to what extent, metal cable trays have a negative influence on the data transfer for 1000Base-T, which allows data rates of up to 1 Gbit/s.

If the cable, in conjunction with the metal surroundings, meets the standard requirements, then the necessary and sufficient condition is fulfilled that the transmission channel is suitable for 1000Base-T. As explained in section 2.1, the criteria of Category 6 (see [4]) are used, which guarantees adequate margins for 1000Base-T.

Because the standard doesn’t set any quantitative limits on the alien crosstalk which arises from electromagnetic coupling to neighboring cables, the requirements for a single cable are also sufficient for the case where the cable is routed in a bundle. For this study, the location of the copper wires of the neighbouring cable is chosen to represent the worst-case scenario for compliance with the standard.

For the sake of completeness, it should be pointed out that the part of the standard (see [4, page 15]) referring to ”Alien crosstalk” indicates that the mutual coupling needs to be taken into consideration for bundled unshielded cables. Specifically: “*The installation of these cables in open trays or ducts requires an additional crosstalk margin in order to guarantee sufficient crosstalk isolation.*” This requirement is fulfilled by the greater NEXT margin provided by the use of the stricter Category 6 standards instead of Category 5. The modeling of the CU 662 cable has shown that the decoupling of the twisted pairs is very good due to the construction of the cables, and the measured crosstalk was largely caused by the connectors used in the measurement. As far as standards conformity is concerned, any critical influence caused by the coupling of cables can be ruled out.

The developed cable model offers a very high amount of flexibility. The size, construction, material and so on of the cable conduit can be changed relatively simply and the influence on the transmission characteristics calculated. Furthermore, a chosen configuration can be studied for various cable lengths. This makes it easy to check compliance to the standards for the specified reference length of 100 m.

In the following images (Figures 31, 35, 36 and 37), the most important transmission properties are shown for some configurations compared to the limits specified in the standard for Category 6 (see [4]).

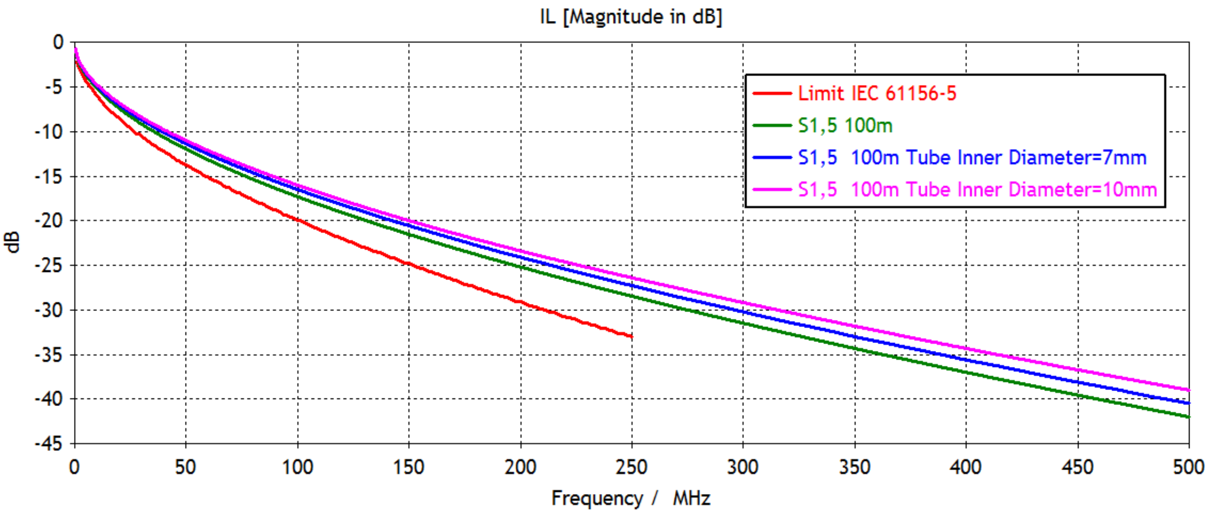

Fig. 31: Insertion loss of the cable model over 100m for the blue pair

It is worth noting that the lowest attenuation in Figure 31 is seen in conjunction with a pipe of diameter of 10 mm – lower than both the case with a thinner pipe and the case with no pipe. This is related to the characteristic line impedance, which as shown in Figures 32-34, reaches the ideal value of 100 Ω for a 10 mm diameter pipe.

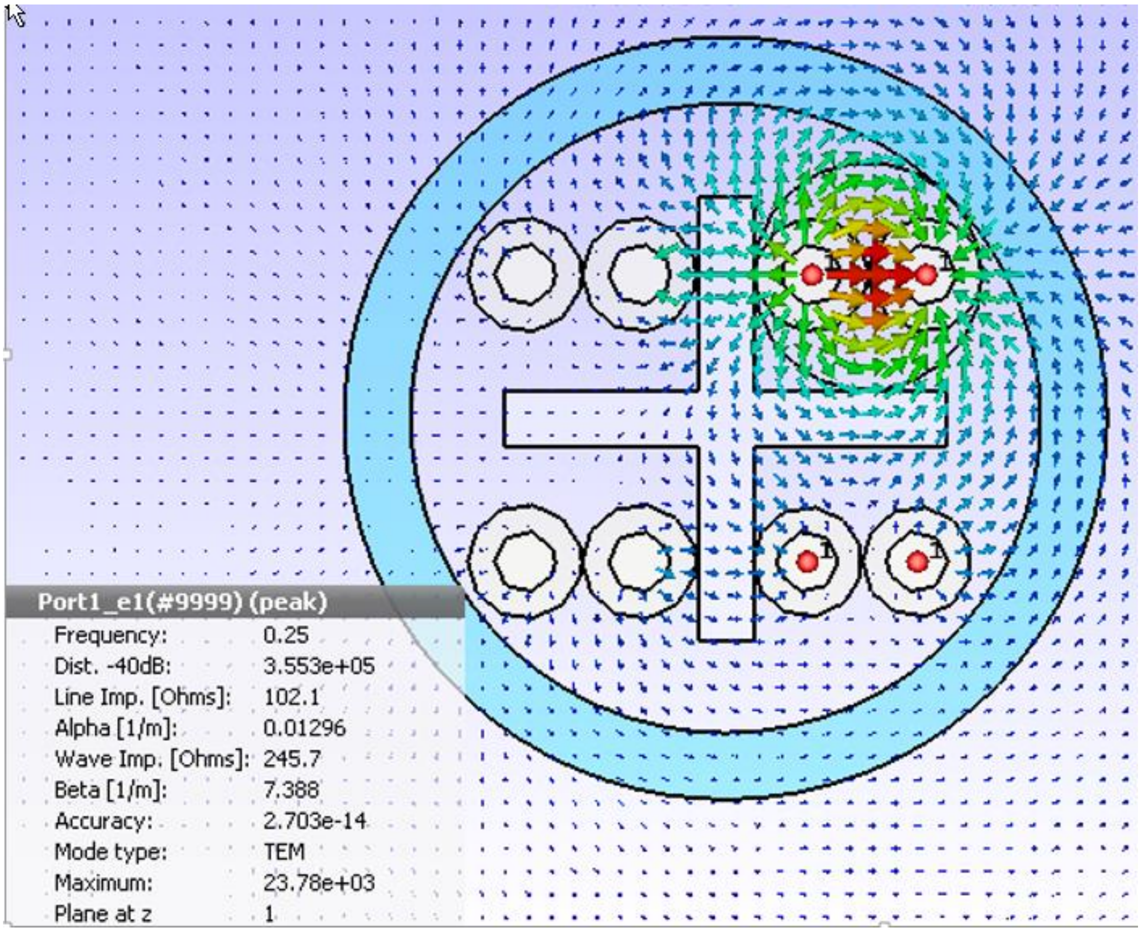

Fig. 32: Impedance (Line Imp. = 102 Ω) of CU 662 without the pipe for the blue pair

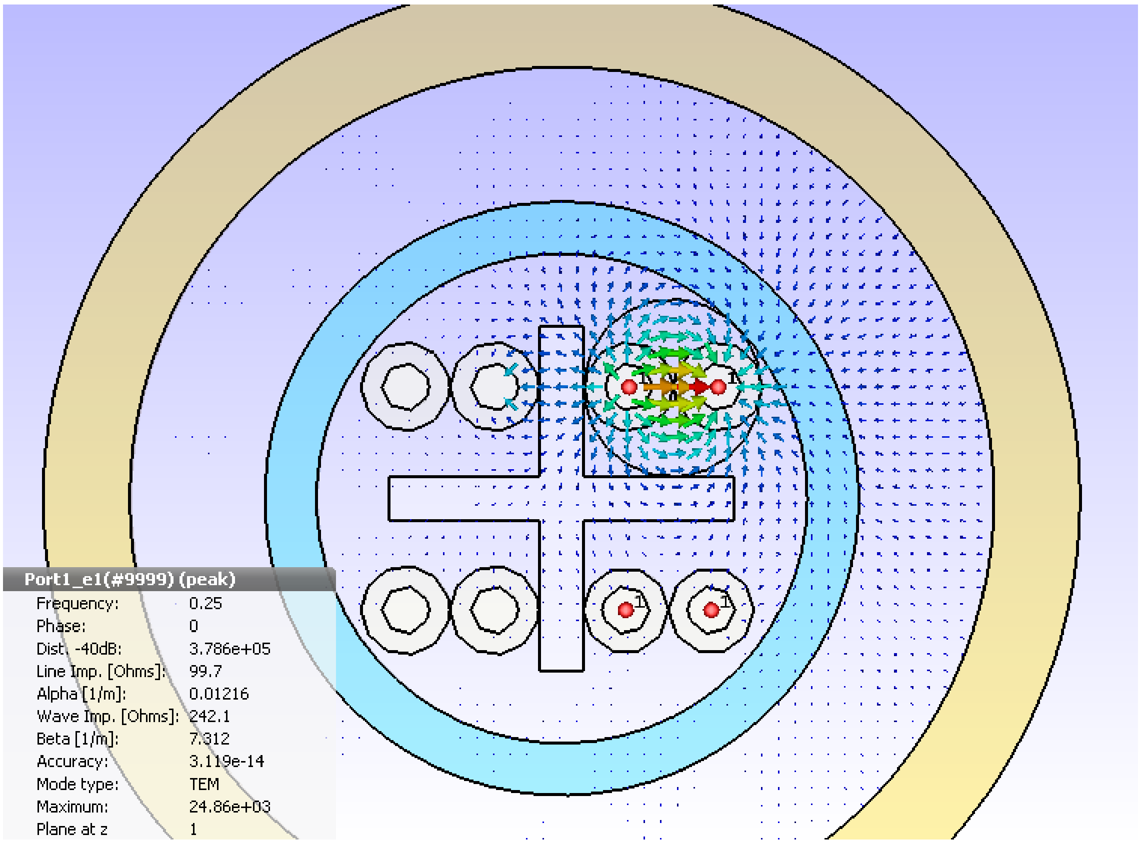

Fig. 33: Impedance (Line Imp. = 100 Ω) of CU 662 in the pipe (Ø10mm) for the blue pair

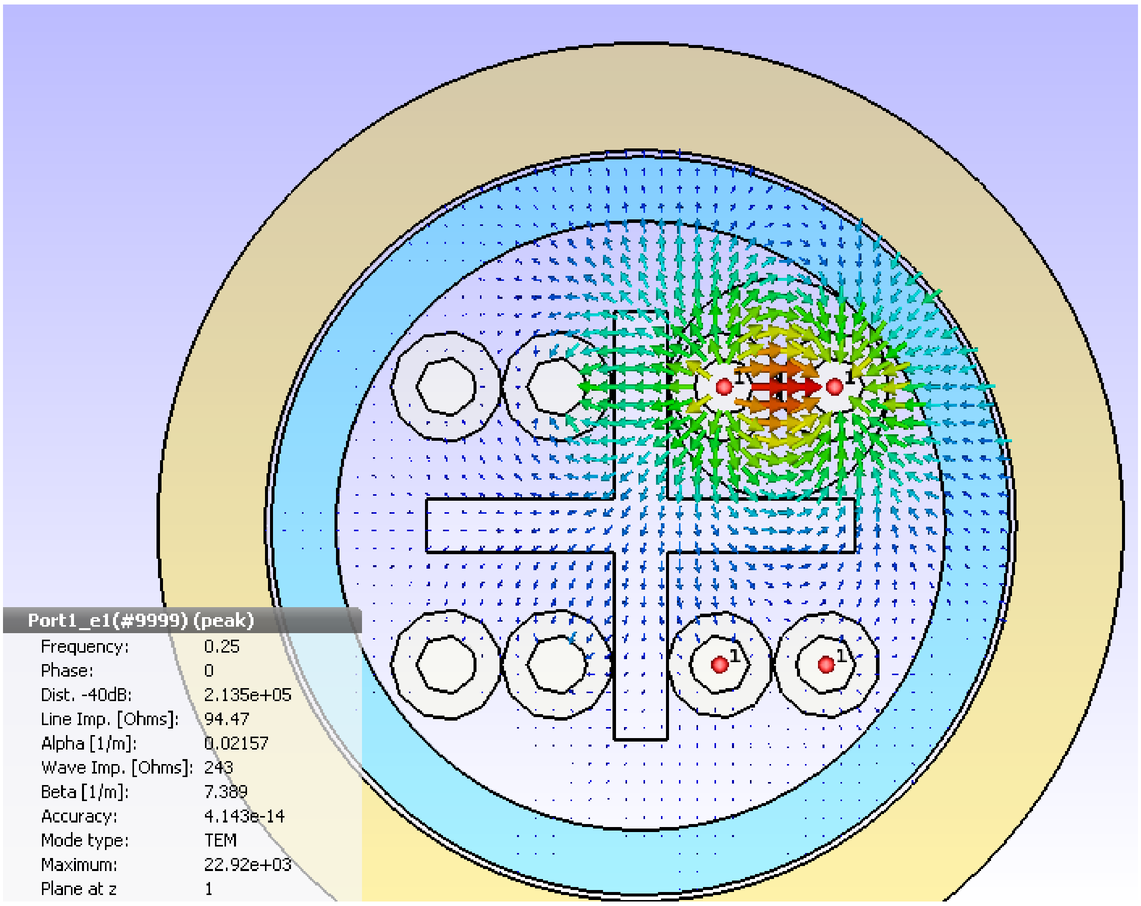

Fig. 34: Impedance (Line Imp. = 94.5 Ω) of CU 662 in the pipe (Ø7mm) for the blue pair

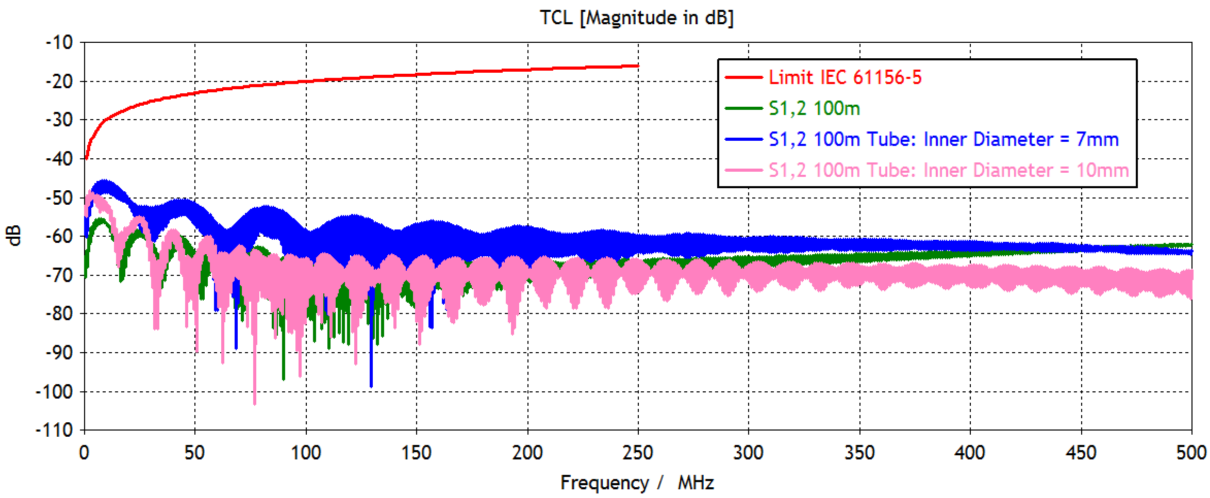

Fig. 35: TCL for the cable model 100m for the blue pair

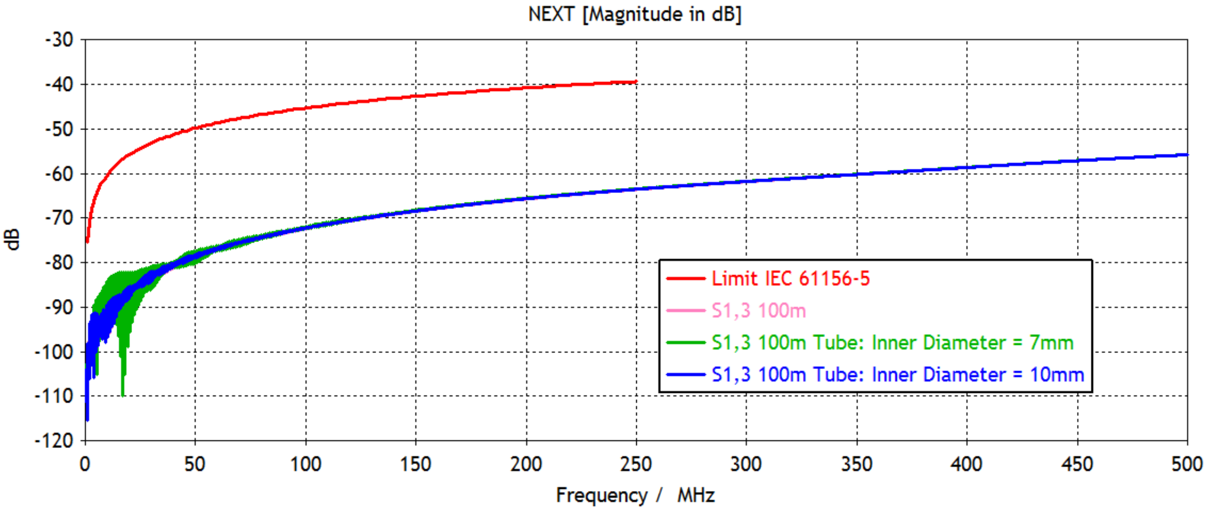

Fig. 36: NEXT for the cable model 100m for the blue pair

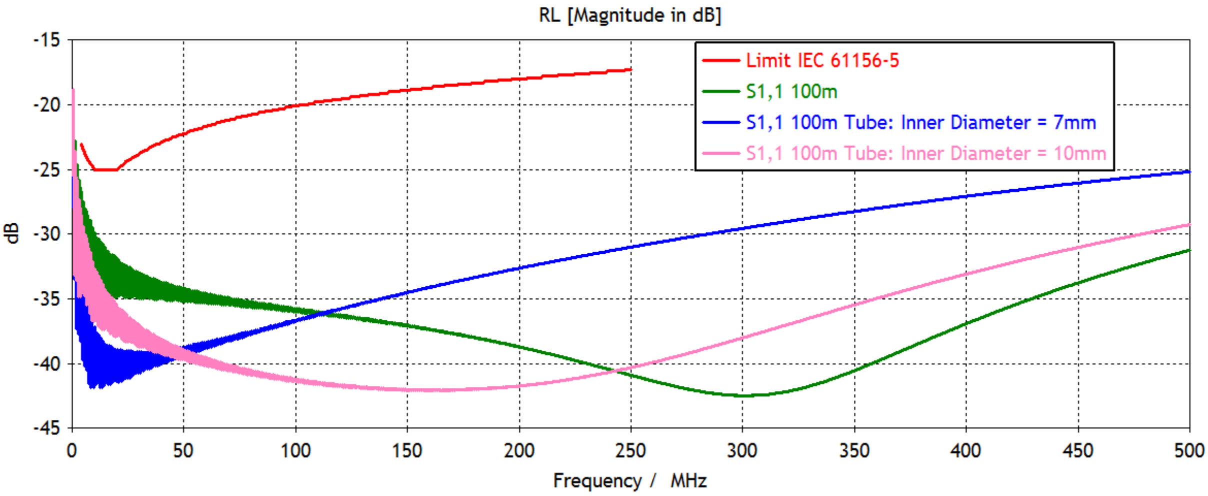

Fig. 37: TCL for the cable model 100m for the blue pair

4. Results

The question posed at the beginning of the study about the influence of metal cable trays can be answered with great certainty: Metallic trays do not interfere with data transfer. In fact, when the cable conduit is taken into account as part of the shielding concept of the cabling, the immunity of the cabling can even be increased because external EMI can have less effect on the cables. This holds even for the extreme case where the conduit is closed tightly around the cable. From this it can be deduced that the bundling of cables will not have a significant influence on the transmission characteristics of the individual cable and is not a critical consideration. An additional look at the imbalance (Figure 37) shows that it is largely unaffected by the surrounding pipe and offers a significant margin against the specified limit. Because the imbalance is an indicator of the coupling of the cables with one another, the idea that the metallic pipe increases the coupling of bundled cables can therefore be ruled out.

As well as answering the main question, this study was also intended to demonstrate the role of simulation in exploring technical questions of this kind. The advantage of simulation and modeling is not only that it reduces experimental work, but also that the abstraction and flexibility that arise from modeling make correlations and interdependencies of mechanical parameters and electrical characteristics clearer and easier to identify. This was especially noticeable when considering crosstalk. It was by no means obvious that the coupling between the pairs in the connector increased despite the separation between them. This result speaks for itself, and does not require further elaboration. The examination of this problem made up a large portion of this study but was presented here in a shortened form in order to keep the scope of this study within reasonable limits. For this reason, we point to reference [6] for further information. A further publication is planned by Mr. Franz Hirtenfelder (CST), who identified this issue, which will explain the details of the crosstalk study more carefully.

Although the cable model offers a convincingly good representation of reality in terms of the derived parameters, it could be argued that the verification of the model could have been more optimal and extensive, and that the model itself could have been further refined in order to obtain deeper and more extensive results. This objection is valid, but a fuller study would have massively exceeded the timeframe that was available. An important goal of this work is also achieved if the applied methodology can serve as a theoretical foundation, offering practical assistance in further studies.