MODELLING OF ATTENUATION AND CROSSTALK OF CASCADED TRANSMISSION LINES

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Abstract. *This paper deals with the measurements and modelling of attenuation and near-end (NEXT) and far-end (FEXT) crosstalk for cascaded metallic transmission lines. The transmission parameters of homogenous metallic line can be easily described by telegraph equations or cascade matrix; there are also several models for NEXT and FEXT frequency dependence. But these models and equations could not be applied in the situation of two or more different cascaded transmission lines, because these cascaded lines do not meet the essential condition of overall homogenous transmission line. However in such case, it is still possible to estimate the overall transmission characteristics of the whole combination thanks to the characteristics of each separate element. This paper brings the description of complex measurements performed for the combination of three different metallic cables and based on these measurements, several conclusions about the possibilities of modelling the attenuation and NEXT and FEXT crosstalk for cascaded transmission lines are presented.*

Keywords

Transmission lines, attenuation, NEXT, FEXT, cascaded lines, modelling.

1. Introduction

The metallic cables are still the most frequent transmission medium for local access telecommunication networks and also local data networks, while they offer decent transmission capacity balanced together with fair costs [1]. The typical access networks usually consist of various different multi-pair and multi-quad metallic cables and they serve as a local data networks or local access telecommunication networks for xDSL digital subscriber lines [2]. Historically, these metallic infrastructures can be composed of various metallic cables with different transmission parameters and characteristics based on their internal construction types (pairs, star-quads, Diesel Horst-Martin quads), wire diameters (typically 0,4; 0,5; 0,6, sometimes even 0,8 or 0,9 mm), types of insulations (PE-polyethylene, PVC-polyvinylchloride, other polymers, paper, etc.), twisting system and radius, etc. [3]. The resulting metallic infrastructure itself can be created by splicing and coupling these various metallic cables with different transmission parameters, therefore it is usually not a homogenous transmission network. Moreover, in the infrastructure itself, there are also splices or mechanical couplings, which are used to mount two metallic cables (actually their particular symmetrical pairs) together and which also influence the resulting transmission parameters [4].

Thanks to that, it is not possible to simply use general formulas, such as telegraph equations or near-end (NEXT) and far-end (FEXT) crosstalk models [5], to calculate the transmission parameters of these cascaded metallic lines. These equations and models are usually valid only for homogenous transmission lines and they are based on an assumption, that the transmission parameters are constant along the whole line and independent on the actual position [6]. But in case of cascading several transmission lines with different transmission parameters, the condition of homogenous line ceases to be valid and the mathematical calculations could become incorrect. This error is significant especially for NEXT and FEXT crosstalk modelling, while the crosstalk couplings are generally different for each combination of symmetrical pairs in a cable and are usually unique for different metallic cables and therefore cannot be approximated for several various cascaded metallic cables without the knowledge of crosstalk in its each element [7].

This paper presents the results of complex measurements performed for three different metallic cables with different constructional and transmission characteristics. Based on these measurements, several general conclusions about the attenuation and NEXT and FEXT crosstalk are proposed. These conclusions are further used to estimate and to calculate the overall attenuation and crosstalk characteristics for cascaded transmission lines based on the results measured and modelled for its each element. These calculations are then compared with measured results and final conclusions about the accuracy of the calculations will be presented.

2. Measurements and Description of Used Metallic Cables

The first cable used for the measurements and modeling was a TCEPKPFLE 75×4×0,4 multi-quad cable from Prakab a.s. production. This cable is typically used for the realization of access telecommunication networks in Czech Republic and for last mile xDSL digital subscriber lines network [8]. It consists of 75 star-quad divided into 3 groups of 25 star-quads each, that means 50 pairs in one. These groups are further divided into 5 subgroups with 5 star-quads each. The diameter of a Cu wire is 0,4 mm, while the insulation is from foamed PE and the interstices between quads are filled with a waterproof gel. The length of a cable used for the measurements was 100 m. The second cable was a standard UTP cat. 5e cable according to the ANSI/TIA/EIA-568-A standard. The diameter of a Cu wire is 0,5 mm and the measurements were performed for a cable with the length of 100 m. And the last cable used for creating cascaded metallic infrastructure was SYKFY 4×2×0,5 cable, again from the portfolio of Prakab a.s. This cable is usually used for local internal infrastructures (phones, data networks, signaling networks) inside large buildings (schools, hospitals, business centers). This cable contains 4 symmetrical pairs with the diameter of a Cu wire of 0,5 mm and PE insulation. The measurements were performed for a cable with the length of 100 m.

The measurements of attenuation, NEXT and FEXT crosstalk and characteristic impedance were performed using Rohde&Schwarz Vector Network Analyzer 10 Hz/9 kHz, 4 GHz-ZVRE, in a frequency band from 100 kHz to 70 MHz. North Hill's balun transformers with impedance ratio 50/100 Ω were used for proper termination and for correct match of the analyzer to the cable. The unused pairs or unused ends of all pairs were properly terminated during the measurements. The attenuation and characteristic impedance (input impedance with opened and short end) was measured for each pair of all three metallic cables individually and also NEXT and FEXT crosstalk attenuation was measured for several combinations of disturbing and disturbed pair.

The critical transmission parameters regarding the digital transmission systems are attenuation and NEXT and FEXT crosstalk (it is also possible to calculate ACR_N, ACR_F – Attenuation to Crosstalk Ratio NEXT, FEXT characteristic) [9]. These parameters can be defined by its attenuation values in dB, or as a ratio between input and proper output signal power as power transfer functions [9]:

$$\begin{aligned}|H(f)|^2 &= 10^{-0,1 \cdot A(f)} \quad [-, Hz; dB]\\ |H_{NEXT}(f)|^2 &= 10^{-0,1 \cdot A_{NEXT}(f)} \quad [-, Hz; dB], \qquad (1)\\ |H_{FEXT}(f)|^2 &= 10^{-0,1 \cdot A_{FEXT}(f)} \quad [-, Hz; dB]\end{aligned}$$

where $|H(f)|^2$ is a power transfer function of a pair, $|H_{NEXT}(f)|^2$ is a NEXT power transfer function between the given combination of disturbing and disturbed pair and $|H_{FEXT}(f)|^2$ is a FEXT power transfer function for the same combination of metallic pairs. The situation and the definitions of these parameters are illustrated in the following Fig. 1.

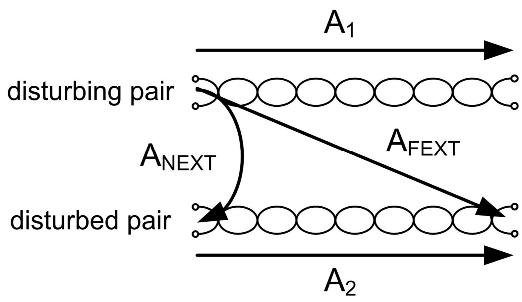

Fig. 1: To the definition of the attenuation and NEXT, FEXT attenuation.

All these power transfer functions are determined exclusively by the proper attenuations (attenuation of a pair, NEXT and FEXT attenuations). Therefore they can be directly calculated using measured values of attenuation, NEXT and FEXT attenuation, or they can be calculated (eventually modelled) by several parameters of given metallic cable and the environment. These formulas are usually mathematically complex (especially for NEXT and FEXT power transfer functions) and they can be found for example in [2]. The characteristics and values of power transfer functions of pairs, NEXT and FEXT power transfer functions used in this article were obtained by measurements of the attenuations for each situation and then calculated by using formulas (1).

The transmission function *H(f)* (either of a pair or NEXT, FEXT crosstalk) has always complex character containing its real and imaginary part. This function is defined by propagation constant $\gamma(f)$ of a pair (which is also complex) or similar NEXT, FEXT propagation complex characteristics having their amplitude and phase components. However, using power transfer function with propagation function's square makes the resulting power transfer function real (it corresponds to the power of a propagating signal). Moreover, when studying NEXT, FEXT crosstalk, the phase characteristic is also usually unnecessary and the power character of a crosstalk is the most important parameter for analyses.

3. Realization, Measurements and Modelling of Cascaded Lines

The first step was the realization of cascaded transmission infrastructure, which consisted from the TCEPKPFLE cable and UTP cable. Four pairs from each metallic cable were connected together using Krone cable distribution frame for proper high-frequency impedance interconnection. The summary length of the cascaded line was 200 m (100 m TCEPKPFLE + 100 m UTP cable). Next picture, Fig. 2, describes this situation together with a definition of attenuation and NEXT, FEXT crosstalk in each element.

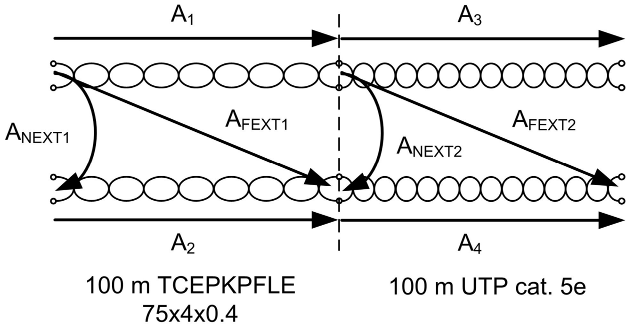

Fig. 2: Cascading the TCEPKPFLE and UTP cable.

The second cascaded infrastructure was composed of TCEPKPFLE 75×4×0,4, UTP cat. 5e and SYKFY 4×2×0,5 cable in this sequence. Again as in the previous situation, 4 pairs from each cable were connected together using Krone distribution frame. The total length was therefore 300 m (100 m TCEPKPFLE + 100 m UTP cable + 100 m SYKFY cable). Figure 3 illustrates the whole situation.

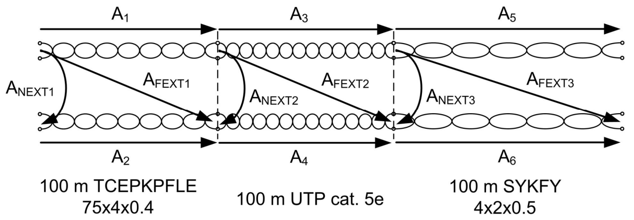

Fig. 3: Cascading the TCEPKPFLE, UTP and SYKFY cable.

3.1. Modelling and Measurements of a TCEPKPFLE and UTP Cascade

The TCEPKPFLE and UTP cables were cascaded according to the Fig. 2. The measurements of attenuation and NEXT, FEXT attenuation were performed from the both side of the cascade. The process of modelling for cascaded transmission lines with different parameters could be quite difficult, while for accurate and exact calculations, many effects should be considered and a complex mathematical model would be necessary [3]. But it is possible to assume several simplifications and conditions, which may simplify the process of modelling, while maintaining sufficient accuracy:

- Impedance mismatches – the characteristic impedance of each cable with different constructional and material parameters is probably different [6]. The direct effect of impedance mismatch in cable joints are reflections and other disturbances. We can assume that the modulus of characteristic impedance in case of typical metallic cables, used for telecommunication purposes, is usually between 90-150 Ω [5]. Which means there are reflections in the point of two cables joining together, but the influence of these impedance mismatches should not be significant, while thanks to the attenuation of a cable these reflections are also partially attenuated.
- Multi-pair and Multi-quad effects – in the case of multi-pair and multi-quad cables, pairs surrounding the signal pair form a Faraday cage, which represents a virtual screen [3]. The signal currents in such surrounded pair induce eddy currents in this virtual screen and represent a further source of loss in the signal conductor.
- Crosstalk via surrounding pairs and quads – the crosstalk in multi-pair and multi-quads cables does not form only between two pairs (disturbing and disturbed pairs), but the crosstalk can be distributed also via surrounding pairs. Again as in the previous simplifications, the influence of this part of a crosstalk could be ignored without a significant effect on the resulting accuracy [5].
- Wavy character of FEXT, NEXT crosstalk – the frequency character of NEXT, FEXT crosstalk contains many dips, peaks and basically it usually shows wavy character. This character is not entirely pseudorandom, but it was proved that it depends on several parameters of a cable and also on the ratio given by the length of a cable and the wavelength of a propagating signal [10], [11]. That's why it is not possible to calculate (model) the exact wavy character of multiple cascaded transmission lines by using their separate NEXT, FEXT characteristics, while the ratio between the length and wavelength is different in each case. The influence of this effect will be probably more significant in case of the measurements performed from the side of a cable with the lowest attenuation (UTP cable in this case). The possibilities of modeling this wavy character of NEXT, FEXT crosstalk will be further studied.

According to the previous simplifications, it is possible to propose a calculation and modelling of cascaded TCEPKPFLE and UTP cables' characteristics based on the measurements of each element. Figure 4 illustrates the methods of calculations.

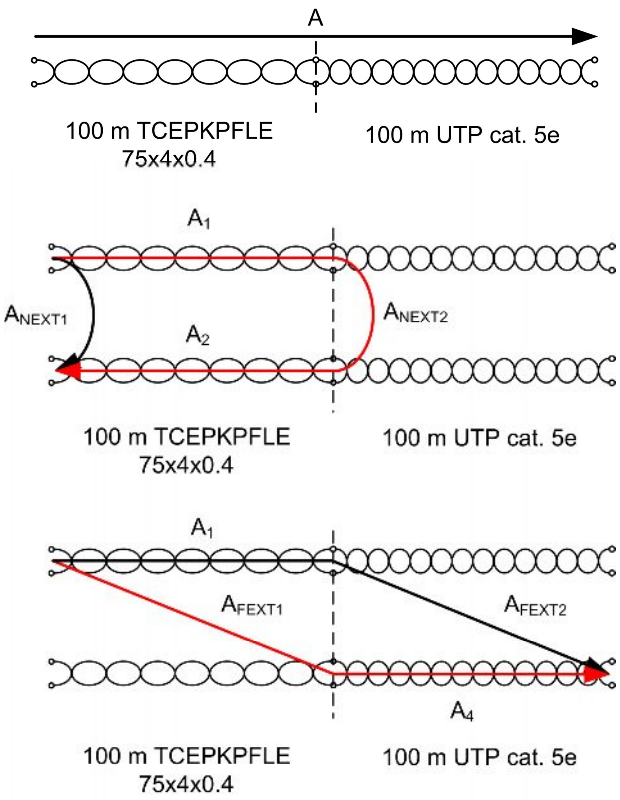

Fig. 4: Calculation of attenuation and NEXT, FEXT attenuation of cascaded TCEPKPFLE and UTP cables.

The equations for calculating the attenuation *A(f)*, NEXT attenuation $A_{NEXT}(f)$ and FEXT attenuation $A_{FEXT}(f)$ can be mathematically defined:

$$\begin{aligned}
&|H(f)|^2 = |H_1(f)|^2 \cdot |H_3(f)|^2 \\
&A(f) = -10\log|H(f)|^2 \quad [dB] \\
&|H_{NEXT}(f)|^2 = |H_{NEXT1}(f)|^2 + |H_1(f)|^2 \cdot |H_{NEXT2}(f)|^2 \cdot |H_2(f)|^2 \\
&A_{NEXT}(f) = -10\log|H_{NEXT}(f)|^2 \quad [dB] \\
&|H_{FEXT}(f)|^2 = |H_{FEXT1}(f)|^2 \cdot |H_4(f)|^2 + |H_1(f)|^2 \cdot |H_{FEXT2}(f)|^2 \\
&A_{FEXT}(f) = -10\log|H_{FEXT}(f)|^2 \quad [dB]
\end{aligned} \quad .(2)$$

The equations for estimations of attenuation and NEXT, FEXT crosstalk for cascaded TCEPKPFLE and UTP cables were implemented into Matlab and the results of the calculations were compared with the measurements. Next Fig. 5 presents an example of attenuation *A(f)*.

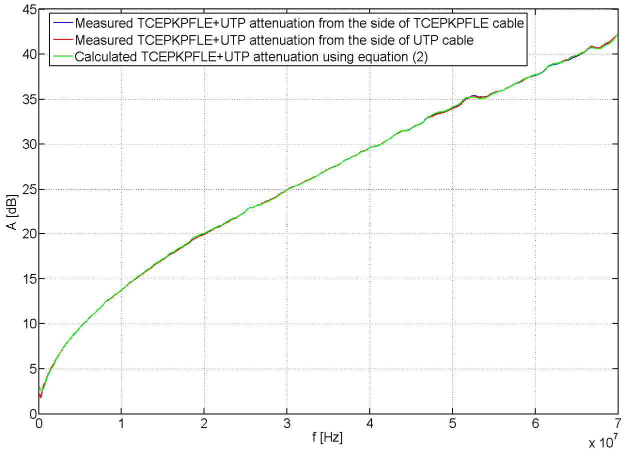

Fig. 5: Comparison of measured and calculated attenuation for TCEPKPFLE and UTP cascade.

It is evident that the attenuation of the whole cascade measured from the side of TCEPKPFLE cable and from the side of UTP cable is practically the same. The calculation of the attenuation based on the equation (2) provides sufficient and accurate results. The reflections and impedance mismatch do not significantly influence the results.

The next Fig. 6 and 7 represents the results of NEXT attenuation measured and calculated according to the formulas (2).

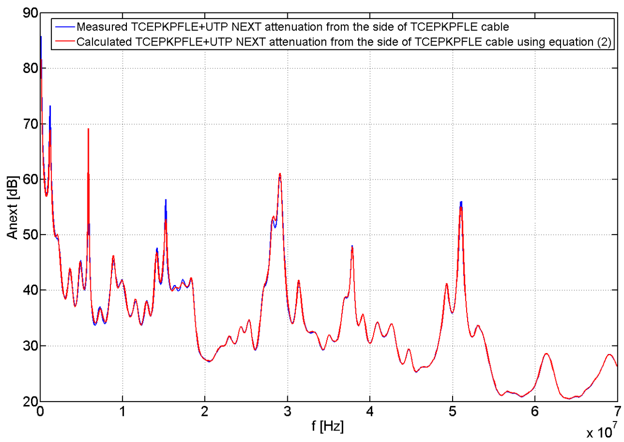

Fig. 6: Comparison of measured and calculated NEXT attenuation for TCEPKPFLE and UTP cascade from the side of TCEPKPFLE cable.

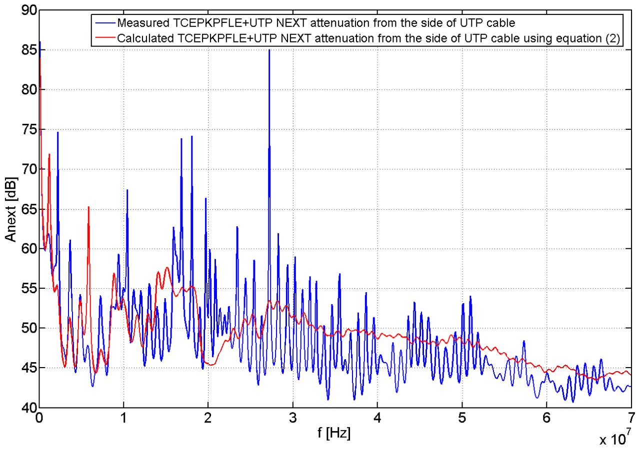

Fig. 7: Comparison of measured and calculated NEXT attenuation for TCEPKPFLE and UTP cascade from the side of UTP cable.

From the comparison between Fig. 6 and Fig. 7 is obvious that the NEXT attenuation is significantly different for the both side of cascaded cables. This is also respected in model (2), because the first part of the summary NEXT attenuation is given directly by the NEXT attenuation of a near element, while the second part of a summary NEXT crosstalk depends on far element, but in addition it is attenuated by the attenuation of a cable. It is also evident that the element with the lowest NEXT attenuation in the whole cascade (TCEPKPFLE cable in this case) plays the dominant role in the summary NEXT attenuation. We can also observe that the measured NEXT characteristic in Fig. 7 is significantly wavier with intensive frequency dips and peaks. This is probably caused by the reflections due to impedance mismatch of both cables and these mismatches are more dominant for UTP NEXT character. A certain role also plays cross-FEXT crosstalk effect, while the reflections on impedance mismatches may propagate to the near-end in form of a FEXT crosstalk as well as direct reflections.

FEXT attenuation measured from both side of a cascade and calculated FEXT using formulas (2) is presented in the following Fig. 8.

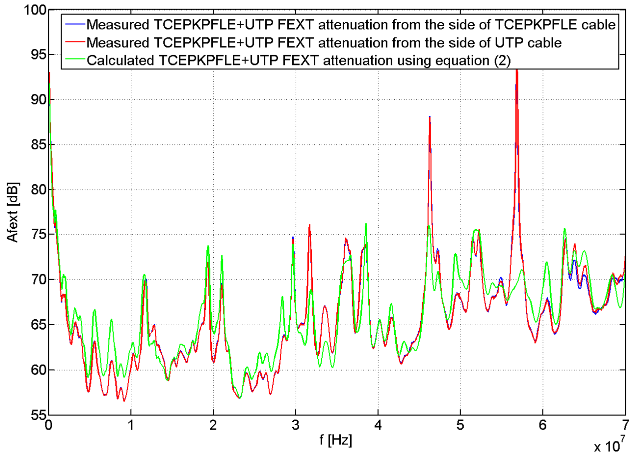

Fig. 8: Comparison of measured and calculated FEXT attenuation for TCEPKPFLE and UTP cascade.

The FEXT crosstalk attenuation is identical from both side of a cascade, as we can see from the measured and calculated results in Fig. 8. The differences between measured characteristics (blue and red lines in Fig. 8) and calculated results (green line) are probably caused due to the simplifications of calculations, which were presented at the beginning of this chapter.

3.2. TCEPKPFLE, UTP and SYKFY Cascade

The previous models and methods for calculating attenuation and NEXT, FEXT crosstalk for cascaded TCEPKPFLE and UTP cable could be used also for further multiple cascading of various metallic cables. For that reason, the cascade from TCEPKPFLE, UTP and SYKFY cable was prepared, measured and modelled. This cascade uses all three metallic cables with parameters presented in chapter 2. The calculation of summary attenuation and NEXT, FEXT crosstalk attenuation for the whole cascade is again based on the characteristics for its each element and these calculations are presented in the next Fig. 9.

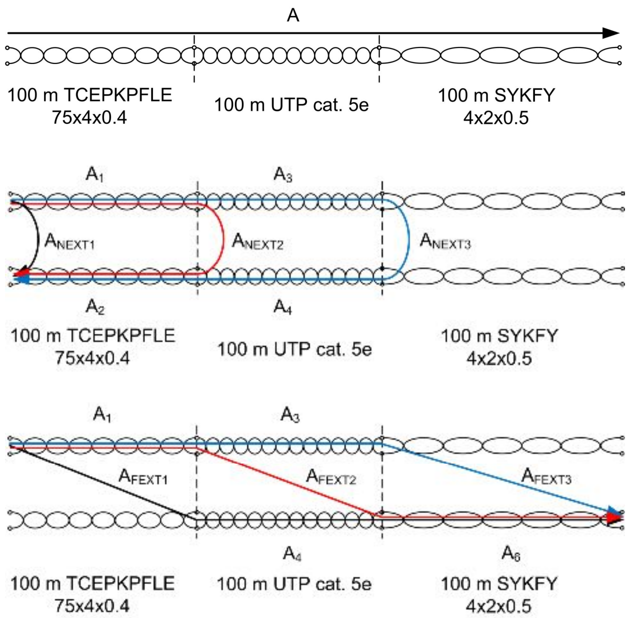

Fig. 9: Calculation of attenuation and NEXT, FEXT attenuation of cascaded TCEPKPFLE, UTP and SYKFY cables.

The cascade models are based only on simple direct crosstalk couplings between all cables. It would be possible to further improve the accuracy of modelling by implementing influence of cross-NEXT and FEXT crosstalk, reflections in cables joining and other effects, but according to the results presented in next graphs, these simple direct calculations provide sufficiently accurate results. The calculation of attenuation *A(f)*, NEXT attenuation $A_{NEXT}(f)$ and FEXT attenuation $A_{FEXT}(f)$ is defined as:

$$\begin{gathered}|H(f)|^2 = |H_1(f)|^2 \cdot |H_3(f)|^2 \cdot |H_5(f)|^2 \\ A_{NEXT}(f) = -10\log|H_{NEXT}(f)|^2 [dB]\end{gathered}, \quad (3)$$

$$|H_{NEXT}(f)|^2 = |H_{NEXT1}(f)|^2 + |H_1(f)|^2 \cdot |H_{NEXT2}(f)|^2 + |H_2(f)|^2 + |H_1(f)|^2 \cdot |H_3(f)|^2 \cdot |H_{NEXT3}(f)|^2 \cdot |H_4(f)|^2 \cdot |H_2(f)|^2$$
$$A_{NEXT}(f) = -10\log|H_{NEXT}(f)|^2 [dB], \quad (4)$$

$$|H_{FEXT}(f)|^2 = |H_{FEXT1}(f)|^2 + |H_4(f)|^2 \cdot |H_6(f)|^2 + |H_1(f)|^2 \cdot |H_{FEXT2}(f)|^2 \cdot |H_6(f)|^2 \cdot |H_1(f)|^2 \cdot |H_3(f)|^2 \cdot |H_{FEXT3}(f)|^2$$
$$A_{FEXT}(f) = -10\log|H_{FEXT}(f)|^2 [dB]. \quad (5)$$

These models were again implemented into Matlab simulation program. The next Fig. 10 illustrates the comparison between measured and calculated attenuation for the entire cascade.

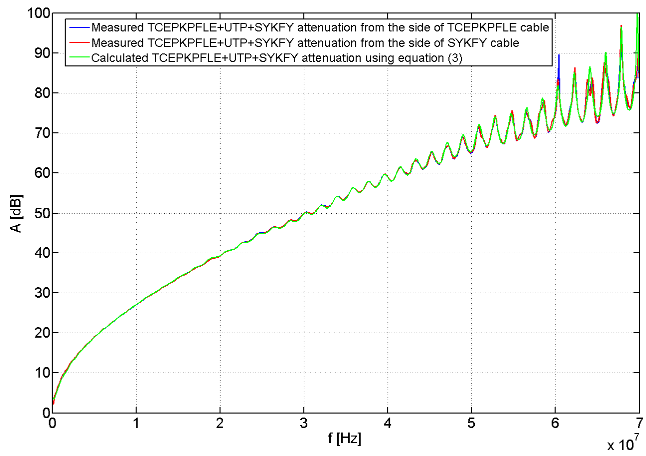

Fig. 10: The measured and calculated attenuation for the whole cascade from TCEPKPFLE, UTP and SYKFY cables.

The attenuation of the entire cascade from TCEPKPFLE, UTP and SYKFY cables with the length of 300 m is influenced mainly by the attenuation of SYKFY cable. This causes the frequency dips and peaks and the wavy character. However, the model shows the same behaviour and it provides realistic result, which is very close to the real measured characteristic. The NEXT attenuation measured and calculated from both side of the entire cascade is presented in next Fig. 11 and 12.

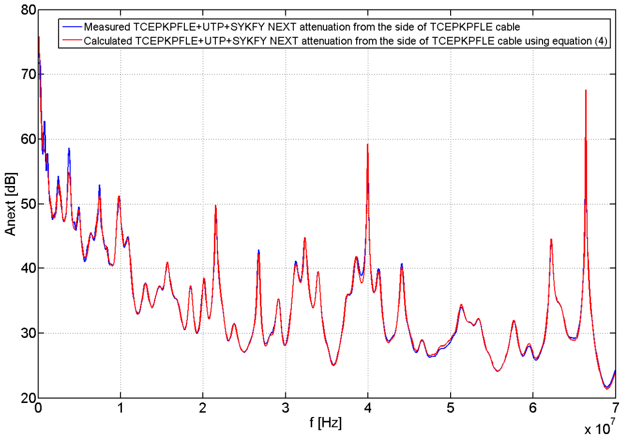

Fig. 11: Comparison of measured and calculated NEXT attenuation for TCEPKPFLE, UTP and SYKFY cascade from the side of TCEPKPFLE cable.

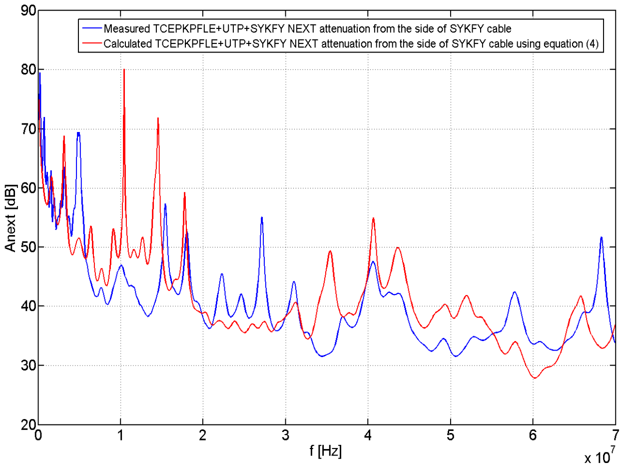

Fig. 12: Comparison of measured and calculated NEXT attenuation for TCEPKPFLE, UTP and SYKFY cascade from the side of SYKFY cable.

The NEXT attenuation measured and calculated from the side of TCEPKPFLE cable is again practically the same, because the NEXT crosstalk of TCEPKPFLE cable is dominant and the rest of the NEXT attenuations in equation (4) have only a minor effect. On the other hand, the NEXT attenuation from the side of SYKFY cable is influenced by all NEXT attenuations (and also by reflections and cross-FEXT effects), so the calculated model is not as accurate as in the previous situation. However, the accuracy of the calculation is still sufficient and it equally estimates the real NEXT characteristic. The FEXT attenuation for the whole cascade measured from both side and calculated from FEXT characteristics of all elements is presented in following Fig. 13.

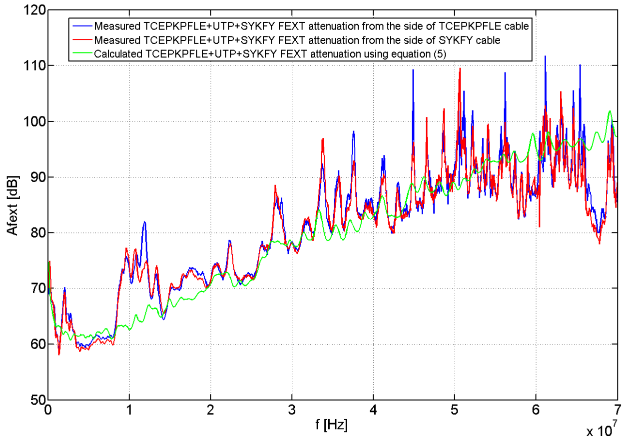

Fig. 13: Comparison of measured and calculated FEXT attenuation for TCEPKPFLE, UTP and SYKFY cascade.

The comparison in Fig. 13 clearly illustrates that the model of FEXT crosstalk due to the several simplifications provides approximate characteristics, which can be used for estimations of FEXT for cascaded metallic cables. On the other hand, the FEXT wavy frequency character depends on the ratio given by the length of the cable and wavelength of a propagating signal [10]. Therefore it is not possible to simulate the exact frequency character of FEXT attenuation for the whole cascade from FEXT characteristics measured for all separate elements.

The standard NEXT and FEXT attenuation models described in [5] can be used to provide the comparison of accuracy between measured NEXT, FEXT attenuation and modelled characteristics of cascaded cables based on formulas (4), (5). The standard NEXT model can be mathematically defined as:

$$A_{NEXT}(f) = k_{NEXT} - 15\log f \quad [dB; dB, MHz], \qquad (6)$$

where $A_{NEXT}(f)$ is an attenuation of NEXT crosstalk, k_{NEXT} is a crosstalk parameter and f is a frequency. If we apply this standard NEXT model (6) on measured and modelled results presented in Fig. 12 we can perform direct comparison of the model's (4) accuracy, which is presented in the following Fig. 14. The k_{NEXT} crosstalk parameters were calculated individually for both characteristics.

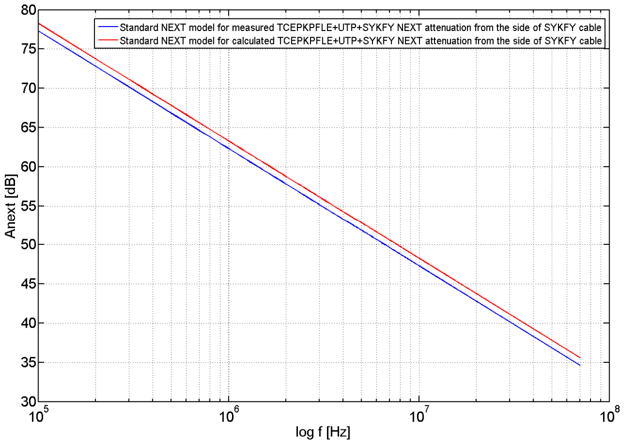

Fig. 14: Standard NEXT model for measured results and NEXT model for calculated NEXT for TCEPKPFLE, UTP and SYKFY cascade.

The comparison between standard NEXT model for measured results and NEXT model for calculated NEXT attenuation of a cascade illustrates that the accuracy of NEXT calculation using formula (4) is sufficient. The difference is approx. 1-2 dB, which is probably caused by the simplifications and other conditions, which were discussed at the beginning of chapter 3.1.

The standard FEXT model comes from the derivation of capacitive and inductive unbalances between two symmetrical pairs and according to [5] can be defined as:

$$A_{FEXT}(f) = k_{FEXT} + A(f) - 10\log l - 20\log f \quad [dB; dB, dB, km, MHz], \quad (7)$$

where $A_{FEXT}(f)$ represents an attenuation of FEXT crosstalk, k_{FEXT} is a crosstalk parameter, $A(f)$ is an attenuation of pair, l is a length of pair and f is a frequency.

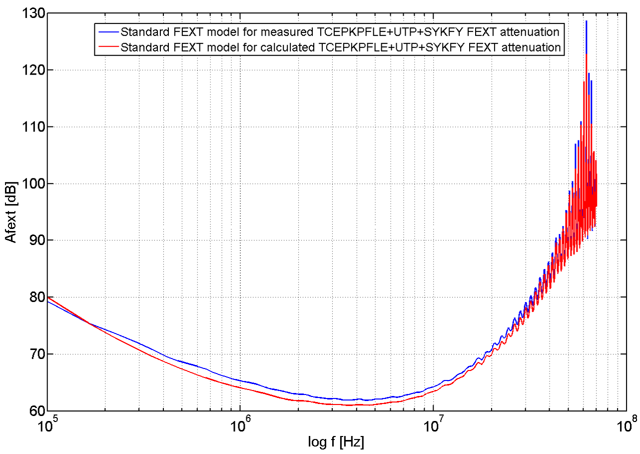

Fig. 15: Standard FEXT model for measured results and FEXT model for calculated FEXT for TCEPKPFLE, UTP and SYKFY cascade.

The Fig. 15 presents the comparison between standard FEXT model for measured results and standard FEXT model for calculated results presented in previous Fig. 13.

In this case we can see that the accuracy of FEXT calculation using equation (5) is acceptable, while the difference between measured FEXT characteristic of cascaded TCEPKPFLE, UTP and SYKFY cables and the FEXT calculated using (5) is less than 1 dB.

4. Conclusion

This paper presented a possibility of calculating and estimating transmission parameters (attenuation, NEXT and FEXT crosstalk) of multiple cascaded metallic cables. These calculations are based on the transmission characteristics of each element in a given cascade. Several simplifications and conditions (especially for neglecting some influences) were applied and the accuracy of this method was discussed and compared using standard crosstalk models. These results were compared with measured characteristics for a cascade realized from TCEPKPFLE, UTP and SYKFY cables. These results clearly confirm that proposed methods for calculating cascaded transmission lines can be applied and used in practical applications to estimate transmission characteristic for multiple cascaded transmission lines and metallic cables with different parameters.

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