Investigation of Accurate Far-End Crosstalk Modeling in Metallic Cables

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Abstract. *Crosstalk and especially far-end crosstalk (FEXT) represents the most serious source of disturbance in today's digital transmission systems. It mostly limits the information capacity of current xDSL digital subscriber lines and also of local data networks with unshielded and or shielded twisted pairs (UTP/STP). The elimination of FEXT will require the implementation of advanced methods for its modeling to obtain required predictions of crosstalk behavior in a cable. The standard simple FEXT model and ITU-T FEXT model are not very accurate and do not provide realistic results. That is why a new method for modeling of FEXT was developed and is presented in this paper. The results of the model are also compared with measured characteristics for a typical UTP cable and several other cables. The proposed advanced FEXT model with minor modifications is applicable for any metallic cable to provide accurate and realistic FEXT characteristics.*

Keywords

Crosstalk, FEXT, modeling, metallic cables, transmission lines.

1. Introduction

The present access telecommunication networks still consist mostly of metallic pairs and cables, which are effectively used for high-speed digital transmission systems, such as digital subscriber lines (xDSL) and Ethernet in the first mile conception (EFM) [1], [2]. The major problem, which appears in large metallic infrastructure, is crosstalk between the digital systems operating within the same metallic cable. The influence of near-end crosstalk (NEXT) can be partially eliminated by frequency duplex method, but the elimination of far-end crosstalk (FEXT) is more complicated [3]. One of the most promising solutions for FEXT cancellation is Vectored Discrete Multi-tone modulation (VDMT) [4]. The implementation of advanced modulation techniques, such as VDMT modulation, usually requires accurate and realistic simulations and estimations of transmission parameters and FEXT transmission characteristics in each situation [5]. That is why a new advanced method of FEXT modeling is necessary to implement. The present standard FEXT model [5] comes only from the averaged crosstalk values for the whole cable and it uses only one crosstalk parameter given for the whole cable [6]. It is obvious that such model cannot be very accurate and that it provides only approximate and not very realistic results, as it was presented in [6]. The similar problem represents the FEXT model presented in ITU-T G.993.5 [8]. The model provides only estimations of FEXT characteristics and its accuracy is not sufficient for the implementation of VDMT modulation.

This paper presents a new innovative method of FEXT modeling based on the conclusions given by extensive measurements performed for a standard unshielded twisted UTP cable and several other metallic cables with different internal structure and parameters. All measured cables are typical examples obtained directly from cables' manufactures. The main idea is the implementation of harmonic functions with arguments equal to the ratio given by the length of a cable and the wavelength of a propagating signal to simulate the dips and peaks in the frequency characteristic of FEXT in real metallic cable. This should improve the accuracy of a model and should provide more realistic results. The results of the proposed model were also verified for other metallic cables with various internal arrangements and parameters.

2. Standard Simple FEXT Model

The standard model for FEXT crosstalk between twisted pairs or quads in a cable comes from the derivation of interactions between them and it results in the elementary formula [5], which can be expressed as:

$$\left|H_{\mathrm{FEXT}}(f)\right|^2 = K_{\mathrm{FEXT}} \cdot f^2 \cdot l \cdot \left|H(f)\right|^2 \tag{1}$$

where $|H_{\mathrm{FEXT}}(f)|^2$ represents the transmission function of FEXT between two pairs, $|H(f)|^2$ is the transmission function of a pair, l is a length of pairs, f is a frequency and K_{FEXT} is a crosstalk parameter (a constant for the given combination of pairs). This parameter presents the rate of crosstalk between selected pairs and it is generally different (unique) for all combinations. In [5] and [6] it is shown that this parameter depends on the mutual position of the disturbing and disturbed pairs in a metallic cable. However, for most applications only one mean value is usually given for the whole cable. It is obvious that this model with only one parameter cannot be very accurate and that it provides only approximate results, as will be presented in next figures.

The ITU-T model, presented in a recommendation G.993.5 [8], is based on the mathematical derivation of crosstalk couplings between symmetrical pairs in a cable and it also uses pseudorandom values of phase characteristic. The model can be expressed, according to [8], as:

$$\left|H_{\mathrm{FEXT}}(f,d)\right| = e^{-\gamma d - j\phi_{\mathrm{k}}(i)} \cdot 10^{-XT_{\mathrm{k}}(i)/20} \cdot \left(\frac{f}{f_{\mathrm{FXT}}}\right) \cdot \left(\frac{d}{d_{\mathrm{FXT}}}\right)^{\frac{1}{2}} \quad (2)$$

where $|H_{\mathrm{FEXT}}(f,d)|$ stands for a FEXT voltage transfer function for frequency f in Hz and FEXT coupling length d in m. $XT_{\mathrm{k}}(i)$ in dB represents the FEXT sample at $f=f_{\mathrm{FXT}}$ and $d=d_{\mathrm{FXT}}$, γ is a propagation constant of a line and $\phi_{\mathrm{k}}(i)$ in rad/m is a uniformly distributed random variable over $[0, 2\pi]$. Variables k, i are, according to ITU-T G.993.5 recommendation, randomly distributed variables, where k is between 1 and 3 and i between 1 and 5 or 1 and 20 respectively. Although the model uses randomly distributed variable, it still does not provide very realistic and accurate results.

The accuracy of these results can be sufficient for some specific applications (for example, summarization of many contributions), but these simple models are not very useful for the precise modeling of perspective VDSL2 lines or EFM. That is why a new modeling method was proposed. To express the attenuation of FEXT in dB, which is more typical, the logarithm of the formulas (1) and (2) is used.

3. Measurements and Initial Conclusions

First, extensive measurements of real metallic cable were performed to obtain necessary results for further conclusions. The measurements were performed for a standard UTP cat. 5e metallic cable according to the ANSI/TIA/EIA-568-A standard (manufacturer: Perfect Signals, LLC) using Rohde&Schwarz Vector Network Analyzer in a frequency band from 100 kHz to 100 MHz. North Hill's balun transformers with impedance ratio 50/100 Ω were used for proper termination and coupling of a cable. The cable was placed and measured in a laboratory (open space) and was arranged in a straight line. The original length of a cable was 264.5 m and after measuring the attenuation of all pairs and FEXT attenuation between all combinations of pairs (4 attenuations, 6 FEXT attenuations), 1 m of a cable was cut and the measurements were performed again. In this way with the step of 1 m, the measurements were repeated until the remain of a cable was only 15.5 m long. Because FEXT crosstalk depends on a length of a cable, it was necessary to perform its recalculation for a reference length according to a formula (3) to be able to compare FEXT characteristics for different lengths.

$$A_{\mathrm{FEXT}}(f)_{\mathrm{ref}} = A_{\mathrm{FEXT}}(f) + 10\log\left(\frac{l}{l_{\mathrm{ref}}}\right) - \left(1 - \frac{l_{\mathrm{ref}}}{l}\right) \cdot A(f) \quad .(3)$$

$$[\mathrm{dB;dB,m,m,dB}]$$

where $A_{\mathrm{FEXT}}(f)_{\mathrm{ref}}$ is the FEXT attenuation for reference length of a cable l_{ref}, $A_{\mathrm{FEXT}}(f)$ is the FEXT attenuation for a cable with measured length l and $A(f)$ is the attenuation of the measured pair. Crosstalk parameter was individually calculated to compare measured results with simple FEXT models (1), (2). Fig. 1, 2 and 3 illustrate measured characteristics, simple FEXT model (1) and ITU-T model (2) for different lengths of a UTP cable.

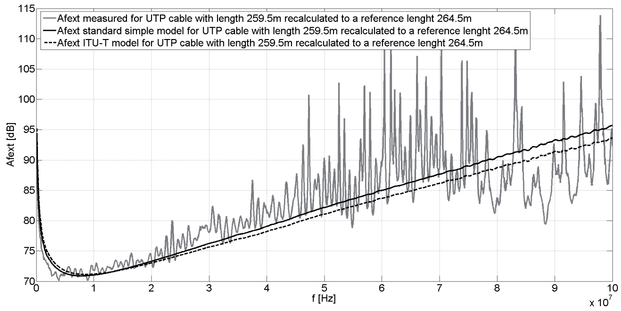

Fig. 1. Measured FEXT attenuation and both FEXT models for a UTP cable with length 259.5 m recalculated to a ref. length 264.5 m.

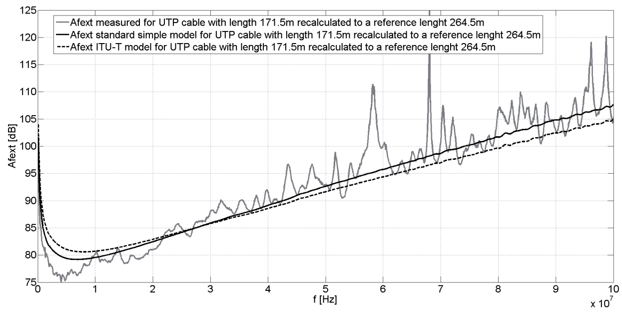

Fig. 2. Measured FEXT attenuation, simple FEXT model and ITU-T model for a UTP cable with length 171.5 m recalculated to a ref. length 264.5 m.

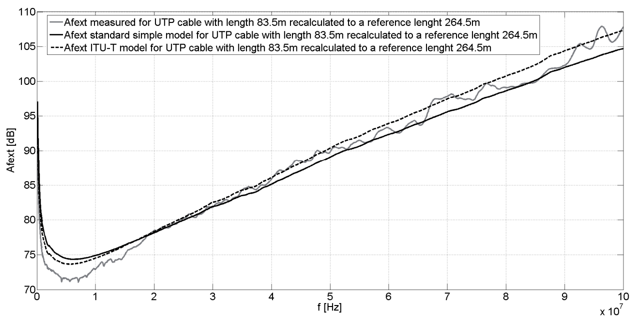

Fig. 3. Measured FEXT attenuation, simple FEXT model and ITU-T model for a UTP cable with length 83.5 m recalculated to a ref. length 264.5 m.

From characteristics in figures above it is evident that the simple standard FEXT model and ITU-T model provide only approximate FEXT estimations without its typical wavy character, therefore the results of these models are not very realistic. The second important conclusion comes from the character of these dips and peaks in measured FEXT characteristics. It is obvious that the wavy character is not entirely pseudorandom, but the period of the peaks and dips is different for various lengths of a cable. It can be concluded that this period of dips and peaks depends on the ratio given by the length of a cable l and the wavelength λ of a propagating signal. While for the length of a cable 259.5 m the FEXT characteristic has plenty of sharp peaks and dips, the same FEXT characteristic for the length of a cable 171.5 m is smoother (the peaks and dips are not so intensive) and the FEXT characteristic for the length of a cable 83.5 m is almost completely flat with only limited number of wide and low curls. The same character of FEXT attenuation was observed for all other pairs and lengths of a cable during the measurements. There are probably also other effects, which could further influence this character – e.g. the accuracy of terminating impedances of both pairs, the ratio of twisting diameter of both pairs, etc., but the context between length l of a cable and wavelength λ of a propagating signal is evident.

The wavelength $\lambda(f)$ of propagating signal could be calculated using a velocity of light in a vacuum, frequency and ε_r, which is a relative permittivity of material used for insulation in a cable [9], and can be derived as:

$$\lambda(f) = \frac{c}{f \cdot \sqrt{\varepsilon_{\mathrm{r}}}} \quad [\mathrm{m;m/s,Hz,-}]. \tag{4}$$

These conclusions were also compared with the ones in [7] and [9].

4. Accurate and Realistic FEXT Model

Based on the previous conclusions and measurements, the improvement of standard simple FEXT model (1) is proposed. The main idea is implementing cosine harmonic functions (either sine or cosine could be used) with arguments equal to the ratio given by the length of a cable l and the wavelength of a propagating signal λ. To maintain the mean value of both cosines nearly zero, one of them must be positive and the other negative with the same amplitude. While the amplitude of a cosine is equal from -1 to +1, the constant K_{NORM} for their scaling must be provided. The value of this constant depends on a twisting ratio of symmetrical pairs, their diameters and resistivity. The summary value of these cosines with the rest of the standard FEXT model could be also negative; therefore the absolute value should be used. The wavelength $\lambda(f)$ is calculated using formula (4).

The resulting advanced FEXT model with all previous conclusions and mathematical notation can be described:

$$\left|H_{\mathrm{FEXT}}(f)\right|^2 = \left|K_{\mathrm{FEXT}} \cdot l \cdot f^2 \cdot \left|H(f)\right|^2 + K_{\mathrm{NORM}} \cdot \left(\cos\frac{2\pi l}{5\lambda} - \cos\frac{9\pi l}{10\lambda}\right)\right| = \left|K_{\mathrm{FEXT}} \cdot l \cdot f^2 \cdot \left|H(f)\right|^2 + K_{\mathrm{NORM}} \cdot \left(\cos\frac{2\pi l \cdot f\sqrt{\varepsilon_{\mathrm{r}}}}{5c} - \cos\frac{9\pi l \cdot f\sqrt{\varepsilon_{\mathrm{r}}}}{10c}\right)\right|. \tag{5}$$

For UTP: $K_{\mathrm{NORM}} = \frac{3}{40 \cdot l^3}$; For PEPKFH: $K_{\mathrm{NORM}} = \frac{28}{40 \cdot l^3}$; For SYKFY: $K_{\mathrm{NORM}} = \frac{12}{40 \cdot l^3}$; For F-02YHQ2Y: $K_{\mathrm{NORM}} = \frac{8}{40 \cdot l^3}$

Using previously presented advanced FEXT model (5) and measured results for UTP cable, several comparisons between the advanced model and measured characteristics for different lengths of a UTP cable were made and are presented in following Fig. 4, 5 and 6.

The proposed FEXT model was also verified for other typical metallic cables for access networks with various internal structures, core diameters and lengths. These measurements were performed thanks to the cooperation with manufacturers – Pražská Kabelovna (Prakab), s. r. o. and Elkond HHK, a. s. The purpose was to verify the validity of the proposed model for cables with various different lengths and also in different frequency bands. All cables were placed and measured in a laboratory (open space) and were again arranged in straight lines. The first measurement was performed for cable PEPKFH 30x2x0.5 (manufacturer: Elkond HHK, a. s.) with the length of 502 m in a frequency band to 30 MHz to verify the validity of proposed model for a cable with different length and in different frequency band compared to the previously presented measurements of UTP cable, an example of results is presented in Fig. 7. The next examples of results were again obtained for cables with different lengths of 102 m and in a frequency band to 100 MHz, SYKFY 4x2x0.5 (manufacturer: Prakab, s. r. o.) in Fig. 8 and F-02YHQ2Y 4x2x0.6 (manufacturer: Prakab, s. r. o.) in Fig. 9. The values of derived K_{NORM} constants for all cables are listed in (5).

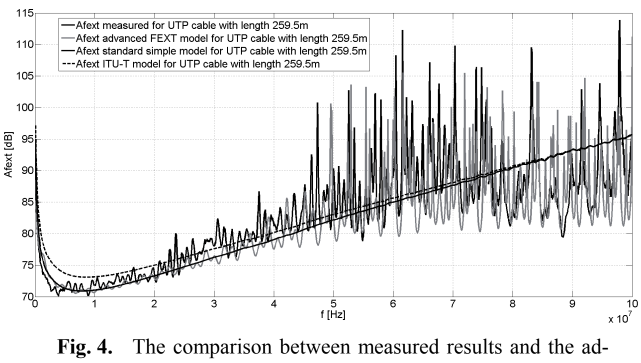

Fig. 4. The comparison between measured results and the advanced FEXT model for the length of a cable 259.5 m.

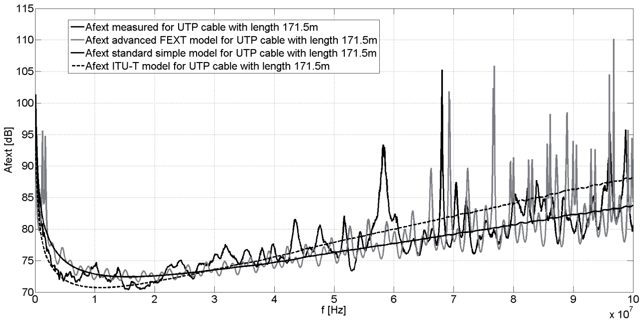

Fig. 5. The comparison between measured results and the advanced FEXT model for the length of a cable 171.5 m.

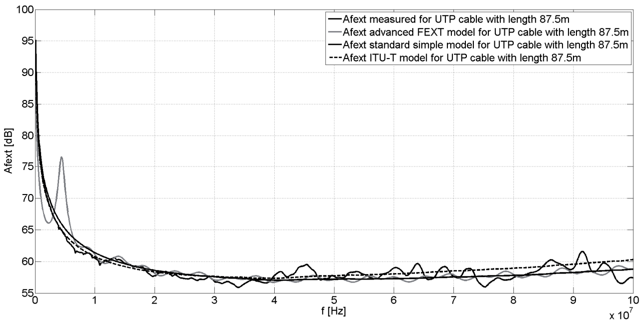

Fig. 6. The comparison between measured results and the advanced FEXT model for the length of a cable 87.5 m.

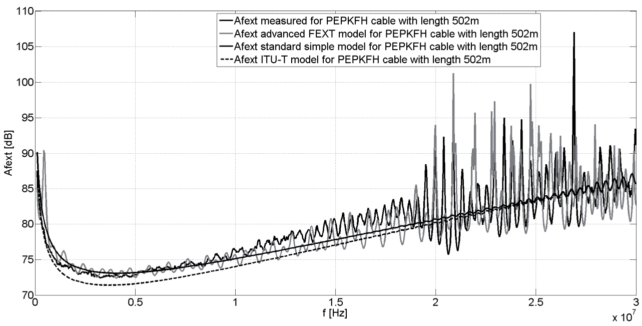

Fig. 7. FEXT models and measured characteristic for PEPKFH cable.

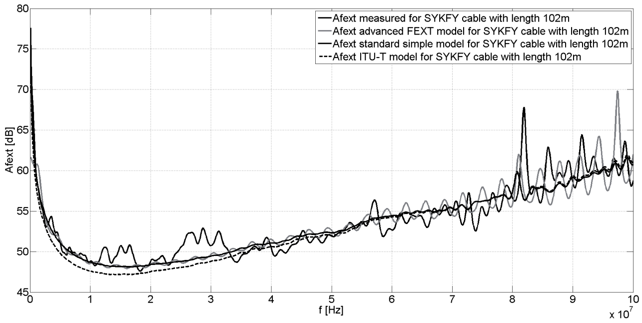

Fig. 8. FEXT models and measured characteristic for SYKFY cable.

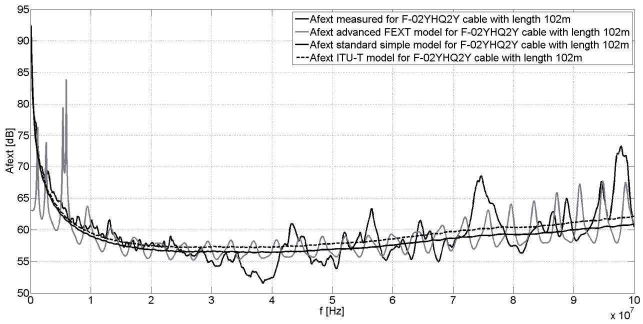

Fig. 9. FEXT models and measured characteristic for F-02YHQ2Y cable.

5. Conclusion

A new method was proposed and designed for simulating and modeling of FEXT transmission functions in real metallic cables. This new model provides above all more accurate and realistic results of FEXT characteristics than a standard FEXT model (1) and ITU-T model (2). Although the model was derived from measurements performed for UTP cable, it could be used for any metallic cable with symmetrical pairs or quads with some minor revisions of proposed constants in formula (5). The results of the model were verified for various metallic cables with symmetrical pairs or quads, such as PEPKFH, SYKFY and F-02YHQ2Y cables. This new accurate model could serve for realistic simulations and calculations of FEXT and to prepare accurate results for the implementation of VDMT modulation into VDSL2 digital lines or simulations of FEXT in EFM networks.

Acknowledgements

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS 10/275/OHK3/3T/13, and also by the grant MSM 6840770014.

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