Generator of Crosstalk Transmission Functions for Modeling of Multi-quad and Multi-pair Metallic Cables

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Anotace:
Přeslechy, zejména přeslech na vzdáleném konci (FEXT – Far-end Crosstalk), představují jeden z nejzávažnějších zdrojů rušení pro současné vysokorychlostní digitální přípojky xDSL (xDSL - Digital Subscriber Line). Vliv přeslechu FEXT se projevuje zejména snížením maximálních dosažených přenosových rychlostí. Pro jeho účinné potlačení bude nutné implementovat pokročilé přenosové techniky a modulace, jako je např. vektorová modulace VDMT (VDMT - Vectored Discrete Multi-tone Modulation). Modulace VDMT však představuje z hlediska nezbytných matematických operací velmi náročný výpočetní proces, který současné výpočetní prostředky v digitálních přístupových multiplexorech DSLAM (DSLAM - Digital Subscriber Line Access Multiplexer) nejsou schopny plně pokrýt. V tomto článku je proto představena možnost využití prostorové selekce rušících systémů v rámci metalického kabelu a omezit tak provádění VDMT modulace jen pro vybraný počet nejvážnějších zdrojů rušení, což by ve výsledku znamenalo snížení náročnosti uvažované metody. Pro účely analýzy přeslechových vazeb mezi jednotlivými páry v kabelu byl navržen nový model přeslechu FEXT označený jako Pokročilý model přeslechu FEXT, vycházející z vnitřního uspořádání kabelových prvků a jejich parametrů. Tento model byl následně implementován v prostředí simulačního programu Matlab a byl použit pro generování pseudonáhodných přenosových funkcí přeslechu FEXT. Vytvořený generátor umožňuje na základě zadaných statistických parametrů a omezeného souboru parametrů přenosového prostředí generovat reálné podklady pro simulace provozu xDSL přípojek s modulací VDMT a pro ověření její schopnosti potlačovat přeslechy za nejrůznějších podmínek bez nutnosti provádět časově náročná měření na reálných kabelech.

Annotation:
Crosstalk, and mainly far-end crosstalk (FEXT), is one the most serious source of disturbance in present xDSL lines (Digital Subscriber Line). It mostly limits the maximum achievable transmission speeds. It is necessary to implement new transmission techniques and modulations, such as VDMT modulation (Vectored Discrete Multi-tone Modulation), for reducing the crosstalk influence. However, the reduction of crosstalk by VDMT modulation is not possible in present systems due to its overall complexity and demands on computational units in DSLAMs. This paper presents the possibility of using space selection of disturbing sources among the metallic cable, which would allow the use of VDMT modulation only for a limited number of the most disturbing pairs. The new far-end crosstalk model, called Advanced FEXT model, which is based on cable's internal structure and parameters, is proposed here. The presented generator of crosstalk transmission functions is based on advanced FEXT model and provides accurate and realistic simulations and calculations of crosstalk characteristics.

INTRODUCTION

Today, xDSL lines (Digital Subscriber Line), e.g. ADSL2+, VDSL, provide cheap and affordable connections mainly for households and small business companies. They use existing symmetrical pairs and local loops of the metallic cables for high speed data transmissions. However, the requirements for the amount of transmitted data and transmission speed are continually increasing and therefore it is necessary to adequately increase the performance of access networks and solutions as it was presented e.g. in [1]. The major problem, which appears in large metallic cables and infrastructures, is crosstalk between the systems operating within the same metallic cable. It comes from unbalanced capacitive and inductive couplings between single copper pairs, their quads and multi-quads as well as from the ground unbalances, [2]. These pairs often demonstrate towards themselves small irregularities, which may be caused by manufacturing tolerances, deformations and other specific reasons. The influence of near-end (NEXT) crosstalk can be well limited by separating transmission directions using different frequency bands, but the reduction of far-end (FEXT) crosstalk is not so easy, and therefore FEXT is the dominant source of disturbance in the present xDSL systems.

Vectored DMT modulation (Vectored Discrete Multi-tone Modulation), presented in [3], is one of the most promising solutions for the elimination of FEXT crosstalk, but its implementation into the present

DSLAMs and other systems is not possible due to its overall complexity and computational demands. One of the possibilities how to simplify the whole process would be performing the vectored DMT modulation only for a limited number of the most disturbing pairs or even only for several xDSL sub-channels, this idea was presented in [4].

This paper describes the method of using space selection of disturbing pairs among the whole cable based on their crosstalk contributions. The first step contains the initial assumptions concerning the allocation of disturbing sources according to the internal structure of the metallic cable, as well as their conclusions resulting from measured characteristics for a real metallic cable. Based on these conclusions, several changes and upgrades of the standard crosstalk model were proposed. The new idea and method for crosstalk modeling was further extended and a new process for generating FEXT characteristics was developed. The paper contains the description of this Advanced FEXT model, the examples of generated FEXT characteristics as well as the examples of measured results.

MEASUREMENTS

This part contains the description of initial measurements and their results; more detailed description of performed measurements was presented in [5]. The measurements were performed for a typical metallic cable, with the specification TCEPKPFLE 75x4x0.4. This cable is filled with a gel and consists of 75 star-quads divided into 3 groups (25 star-quads each). Each group contains 5 subgroups of 5 star-quads (10 symmetrical pairs), which are arranged into the pentagonal orientation. The measurements were performed for a frequency band to approx. 34.5 MHz (with the consideration of VDSL2 systems) and the frequency steps were selected as the multiplies of the xDSL channel intervals (4.3125 kHz). One pair was always selected as a disturbing one and the FEXT contributions were taken from the rest pairs one by one. All other pairs were properly terminated. The measurements were performed for only one subgroup of pairs (50 pairs).

The analysis of measured results was focused on the determination of the crosstalk contributions between different combinations of disturbing and disturbed pairs in the cable.Power spectral density (PSD) was considered to be constant for the whole frequency band and its value responds to -60 dBm/Hz (VDSL2 systems). Fig. 1 presents an example of results for the disturbed pair number 4.

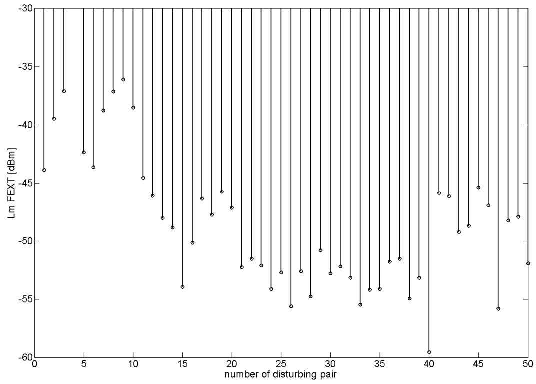

Fig. 1: The FEXT contributions of all disturbing pairs.

Based on these results, some conclusions about the allocation of disturbing sources in the cable can be made:

- Within the framework of one star-quad (here pair number 3) is the level of crosstalk practically the same as is the crosstalk level from the other pairs in the same subgroup (here pairs number 1-10).
- The crosstalk between pairs among one subgroup is indeed in the most cases dominant source of FEXT (here pairs number 1-10).
- Subgroups, which are located in the cable in a close proximity (here pairs number 11-20 and 41-50), are participating more in the total crosstalk level, than the distant subgroups placed on the opposite side of the cable (here pairs number 21-40).

The summary conclusion of these measurements is that there are significant differences between the crosstalk contributions of each constructional category of the cable – pairs in the same subgroups, pairs in the close subgroups and pairs in the far subgroups. It would be possible to use the relative position of disturbing and disturbed pairs for more accurate simulations of FEXT. These results were also compared with conclusions given in [6].

STANDARD FEXT MODEL

The standard model of FEXT crosstalk in metallic cable, description in [7], comes from the derivation of capacitive and inductive couplings between pairs and it results in the elementary formula (1). To express the attenuation of FEXT crosstalk in dB, which is more typical, the logarithm of the (1) is used.

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

Where $|H_{FEXT}(f)|^2$ represents the transmission function of the FEXT crosstalk, $|H(f)|^2$ is the transmission function of a pair, f is the frequency, l is the length of the pair. K_{FEXT} is a crosstalk parameter (a constant for the selected combination of pairs), which represents the rate of capacitive and inductive couplings between selected pairs and this parameter is generally unique for all combinations of pairs. However, for the most situations, only one mean value of this constant is usually given for the whole cable. The Fig. 1 presents, that there are significant differences between crosstalk levels for different combinations of pairs, which are resulting from the relative positions of these pairs in the cable. It is obvious that the standard model with only one parameter cannot be very accurate and that this model gives only approximate results. The accuracy of this model could be sufficient for example in case of summarization of many contributions. But it is not acceptable for individual modeling of FEXT crosstalk between pairs in a cable, which will be necessary for the implementation of VDMT modulation and future applications. That is why the new modeling method was proposed.

ADVANCED FEXT MODEL

The new method for accurate and realistic FEXT simulations was proposed. This Advanced FEXT model takes into consideration the relative position of disturbing and disturbed pair in a cable, so its accuracy is much better. This idea was further extended and a new process for generating FEXT characteristics, which are very realistic and close to the real situations in metallic cable, was developed. This procedure allows generating pseudorandom characteristics under different and various conditions, implemented mathematical model allows the use of the Advanced model for various types of metallic cables and environments. The whole process is described in following Fig. 2.

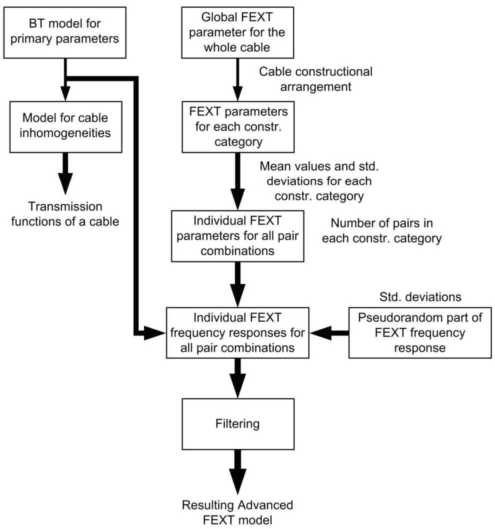

Fig. 2: The process of generating advanced FEXT model characteristics.

The transmission functions of symmetrical pairs are calculated using British Telecom model (with 13 parameters), which is described e.g. in [7]. They are supplemented by pseudo-randomly generated components, which simulate inhomogenieties, deformations and other imperfections. Then, it is necessary to calculate K_{FEXT} parameters of crosstalk for all constructional categories and individually for all combinations of pairs in a cable. Afterwards, K_{FEXT} mean values and standard deviations of normal distribution are calculated for each constructional category. In this case, these statistical values were determined from the measured results and by subsequent statistical evaluations. The model is further supplemented by pseudo-randomly generated components of frequency responses, the necessary statistical parameters were obtained by comparing the generated characteristics of the model with measured results. In the last step, the model with these pseudorandom elements is filtered in order to eliminate spectral components exceeding real characteristics. Thanks to the previous conclusions concerning the cable's internal structure, it was possible to reduce the number of necessary parameters for the Advanced FEXT model by grouping them according to their relative positions in the cable. The model, its parameters and results, which are presented in this paper, were calculated and derived for a specific metallic cable (description in the previous section), but the mathematical model for this new modeling method is valid for any metallic cable with multi-pair or multi-quad construction.

The mathematical description of Advanced FEXT model comes from the standard model (1) and is based on the general model of transmission channel in xDSL systems using DMT symbols (2).

$$\mathbf{Y} = \mathbf{H}^C \cdot \mathbf{X} + \mathbf{w}$$

$$\left(\left[Y_n(i)\right]_{i=1}^{m}\right)_{n,1} = \mathbf{H}^C \cdot \left(\left[X_n(i)\right]_{i=1}^{m}\right)_{n,1} + \left(\left[w_n(i)\right]_{i=1}^{m}\right)_{n,1} \quad (2)$$

Where **Y** represents the output matrix of frequency vectors of received DMT symbols for all n channels, **X** stands for one-column matrix of frequency vectors of input DMT symbols, **w** is one-column matrix of noise vectors containing frequency vectors of the disturbance from all surrounding channels not coordinated by VDMT modulation and finally, matrix **H** (generally complex) is a square matrix of n,n dimension containing frequency vectors of transmission functions (channels and FEXT crosstalk). The equation (2) is valid if cyclic prefix (CP) has sufficient length, also the perfect synchronization of input symbols is necessary and the transmission channel must have pulse response shorter than CP.

The matrix of transmission functions **H** can be divided into two sub-matrixes, a diagonal matrix of transmission channels $\mathbf{H}^{Ch}$ and a remaining matrix of transmission functions of FEXT crosstalk $\mathbf{H}^{F}$ (3).

$$\mathbf{H}^C = \mathbf{H}_{Ch}^C + \mathbf{H}_F^C \quad (3)$$

Symmetrical pairs in a typical metallic cable usually provide similar transmission characteristics, minor differences between them are implemented in further process of pseudorandom generating and simulation of channel inhomogeneities. Thanks to this assumption and using mathematical operation called Hadamard product, it is possible to simplify the matrix $\mathbf{H}^{Ch}$ and to express it using identity matrix $\mathbf{E}$ and one frequency vector for all n channels.

The matrix of transmission functions of FEXT crosstalk $\mathbf{H}^{F}$ can be expressed using the equation of standard model (1) for all combinations of pairs, here e.g. for pairs number 1, 2, and using Hadamard operation as (4).

$$\left[H_{12}^{F}(i)\right]_{i=1}^{m} = K_{12}^{FEXT}\cdot l\cdot\left[f^{2}(i)\right]_{i=1}^{m} * \left[H^{Ch}(i)\right]_{i=1}^{m} \qquad (4)$$

Several operations for generating pseudorandom parameters and characteristics were used during the process of presented Advanced FEXT model. These operations are based on statistical parameters of normal distribution, which were calculated using measured results and characteristics. These pseudorandom components are supplemented to the previously described matrixes and vectors. These matrixes with pseudorandom parts are marked with circumflexes, pseudorandom matrix $\mathbf{\Delta}^{F}$ contains generated components of FEXT crosstalk between channels and the frequency vector $\mathbf{\Theta}$ contains vectors of randomizing parameters for all n channels.

$$\overline{\mathbf{H}^{C}} = \left[H^{Ch}(i)\right]_{i=1}^{m} * \left\{\begin{array}{l} l\cdot\left[f^{2}(i)\right]_{i=1}^{m} * \overline{\mathbf{K}_{F_{n,n}}} + \\ + \left[\left[\Theta_{n}^{Ch}(i)\right]_{i=1}^{m}\right]_{n} * \mathbf{E}_{n,n} \end{array}\right\} + \mathbf{\Delta}_{F_{n,n}} \qquad (5)$$

RESULTS

Equation (5) represents the final mathematical description of Advanced FEXT model. This model respects the influence of relative position of disturbing and disturbed pair in the cable as well as contains generated pseudorandom characteristics for accurate and realistic results, which are very close to real characteristics of FEXT in metallic cable.

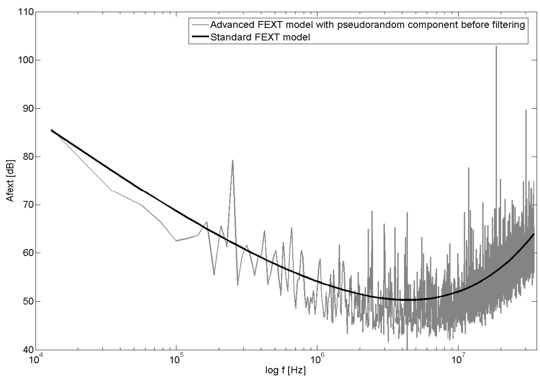

Fig. 3: The comparison of standard FEXT model and advanced FEXT model before the filtering.

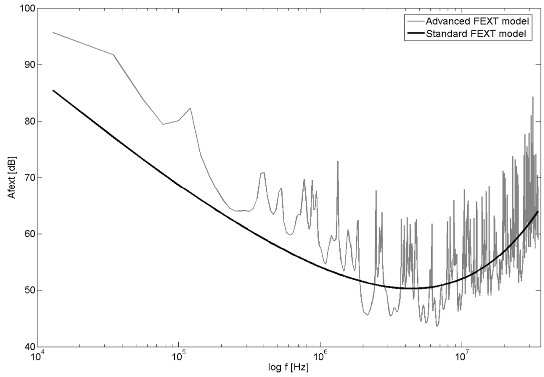

Fig. 4: The comparison of standard FEXT model and advanced FEXT model after the filtering.

Previous characteristics in Fig. 3 and 4 provide an example obtained using the presented method of Advanced FEXT model and process of generating FEXT characteristics by designed pseudorandom FEXT generator. It is obvious that unlike the standard FEXT model (presented in the graphs as a black line), the proposed Advanced modeling method provides more precise and realistic results. The standard model comes from only average values for the whole cable, the Advanced method based on statistical evaluations and internal structure of the cable provides final results very close to the characteristics in real applications.

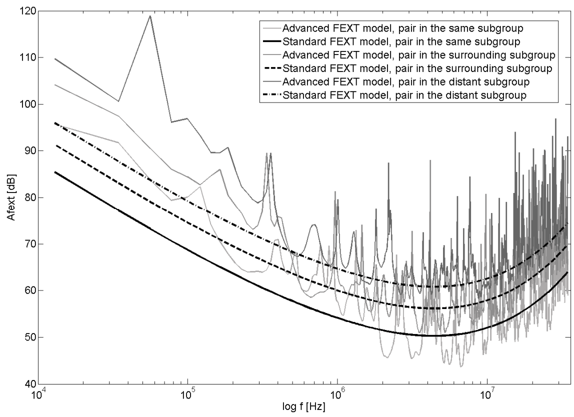

Fig. 5: The comparison of standard FEXT models and advanced FEXT models for different pairs with different relative positions.

Fig. 5 confirms previous assumptions about the influence of relative position of disturbing and disturbed pair on resulting crosstalk level. The graph contains the comparison of FEXT attenuation for three different combinations of pairs with the different relative positions each. The results demonstrate that there are significant crosstalk differences between proposed constructional categories and that the relative position of disturbing pairs in a cable has a significant effect on the total crosstalk level.

Tab. 1: K_{FEXT} statistical parameters used in Fig. 5.

K_{FEXT}	Mean value	Variance
The same subgroup	$3.1213.10^{-17}$	$1.3836.10^{-33}$
Surrounding subgr.	$8.0778.10^{-18}$	$1.8584.10^{-35}$
Distant subgroup	$3.6712.10^{-18}$	$2.2243.10^{-36}$

Previous Tab. 1 shows statistical parameters of normal distribution used for generating the pseudorandom FEXT characteristics (Fig. 3, 4, 5).

CONCLUSIONS

This paper presented the new method for simulations and modeling of FEXT transmission functions in multi-pair or multi-quad metallic cables. The Advanced FEXT model was further implemented into the new pseudorandom generator of crosstalk transmission functions. The generator uses the Advanced FEXT model, which is based on detailed analyses of the metallic cable, its internal structure, constructional arrangement and parameters. The model takes into a consideration the relative position of disturbing and disturbed pairs in the cable and thanks to that provide more accurate results and simulations of FEXT characteristics. Implemented pseudo-randomly generated components make resulting FEXT transmission functions more realistic. The necessary statistical parameters were obtained by complex statistical evaluations of measured results. The number of parameters used in Advanced FEXT model was reduced by dividing the cable into three constructional categories and by grouping these parameters according to the relative positions in the cable.

The calculated results and generated characteristics obtained using this model and generator are very realistic and very close to crosstalk characteristics in real metallic cable. These results could be also used for the analyses of the VDMT modulation's ability to reduce FEXT crosstalk under different conditions without performing necessary measurements of real metallic cables.

ACKNOWLEDGMENT

The whole research and this paper were supported by the grant MSM6840770014.

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