

FAR-END CROSSTALK MODELING BASED ON CAPACITIVE AND INDUCTIVE UNBALANCES BETWEEN PAIRS IN A CABLE

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Abstract. *This article deals with new ways of far-end crosstalk (FEXT) modeling in multi-pair and multi-quad metallic cables. Current standard modeling methods provide only rough estimations of FEXT characteristics based on average values of crosstalk for the whole cable. However, for practical implementation of vector discrete multi-tone modulation (VDMT) is necessary to predict and simulate FEXT characteristics with sufficient accuracy and simulate FEXT transfer functions individually for each combination of symmetrical pairs in a cable. This article contains a theoretical analysis and description of the problem and suggests a new method for modeling of FEXT crosstalk using capacitive and inductive unbalances between pairs in a cable. This proposed model offers more accurate and realistic results of crosstalk. Theoretical simulations and results are also compared with the measured characteristics for specific metallic cable.*

Keywords

Crosstalk, FEXT, transmission line, VDMT, xDSL.

1. Introduction

The crosstalk can be generally described as a negative phenomenon, when a part of the signal transmitting at the disturbing line penetrates through inductive and capacitive couplings to the parallel disturbed pair [1]. The influence of near-end crosstalk (NEXT) can be well limited by separating transmission directions by using different frequency bands, but the reduction of far-end crosstalk (FEXT) is not so easy and therefore FEXT is a dominant source of disturbance in current xDSL lines and it significantly reduces the maximum transmission speed achieved by these systems [2]. The standard model of FEXT crosstalk is based only on average values of crosstalk across all pairs and their combinations for the whole cable. It uses only one crosstalk parameter given for the whole cable so it is obvious that such model

cannot be very accurate and that it provides only approximate and not very realistic results, as presented in [3], allowing only limited estimations of its impact on the resulting system response. One of the most promising solutions for the elimination of FEXT is Vectored DMT modulation (VDMT) for VDSL2 connections. However, this method requires very accurate prediction of crosstalk behavior and realistic modeling of FEXT for all combinations of pairs in a cable and individually for each transmission channel [4].

This paper presents a new innovative method of FEXT modeling, which is based on simulations and calculations of capacitive and inductive unbalances between pairs in a cable and using cascade matrices of a transmission line. The first part is focused on derivation of a general description of the current situation and crosstalk currents for a pair of symmetrical pairs located within a copper cable. This derivation will also be compared with the formulas of the standard model of FEXT crosstalk, as presented in [5]. The next part deals with the implementation of a new method for modeling FEXT crosstalk. This model will respect the internal structure of a cable and will consider the value of the variable capacitive and inductive coupling between pairs along the length of a cable. The results of simulations will be also compared with standard FEXT model as well as with measured results for the cable with TCEPKPFLE specification.

2. General Expression of Far-End Crosstalk Currents in a Cable

The elementary unit of a standard telecommunication cable is generally two insulated wires twisted uniformly to form a balanced pair. By twisting four insulated wires together uniformly a star-quad is formed. Several quads are typically twisted together to form a subgroup of pairs (or quads), these subgroups can be further twisted and gathered according to a cable's internal structure and they can be also covered with screening, sheeting or taping to form grounded shielding and to separate each subgroup of pairs. Interstices between pairs, quads and subgroups

are usually filled with a gel or air [6]. During the process of cable's manufacturing, several parameters have to be measured and checked, and must meet specified tolerances. Based on these tolerances, pairs, quads and subgroups in a cable demonstrate towards themselves small irregularities and unbalances. These unbalances are caused mainly by irregularities of conductors and dielectric, defects of dimensions and positional differences of conductors, wires, pairs and quads. The second part of these unbalances comes from cable's inappropriate placing, external or internal deformations and some random influences. Capacitive and inductive unbalances and couplings are the main source of crosstalk between them. These capacitive and inductive couplings in a quad of four wires form an unbalanced bridge [7]. Using the star-polygon transformation it is possible to express resulting capacitive unbalance C_{ub} and inductive unbalance M_{ub} . The calculation of these unbalances is based on the geometrical structure of the quad and other parameters, such as permittivity and permeability of the materials. In this case, the C_{ub} unbalance is calculated using four individual capacitive unbalances between single conductors, therefore it is equal to $4 \cdot \Delta C_{(13,14,23,24)}$ of these unbalances [15]. The impact of inductive coupling can be modelled by an additional capacitance unbalance and both capacitive and inductive parts can be included in the summary capacitive unbalance C' [8].

The far-end crosstalk is caused by disturbing currents, which penetrate from the disturbing pair to the parallel disturbed pair, thanks to the capacitive and inductive unbalances between them. This situation is described in the next schematic.

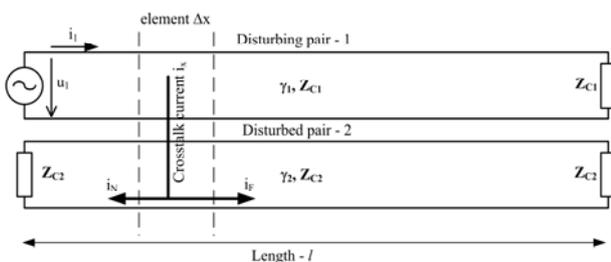


Fig. 1: The schematic situation of parallel disturbing and disturbed pairs.

We can assume the situation with two parallel pairs in a cable, where the near-end of the disturbing pair contains the source of signal u_1 with total current i_1 . The pair is correctly terminated on its far-end by the characteristic impedance of this pair Z_{C1} . The disturbed pair is properly terminated on its both ends by its characteristic impedance Z_{C2} . The propagation constant of disturbing pair is γ_1 , while the propagation constant of disturbed pair is γ_2 . The length of both pairs is l . The infinite element Δx contains a total capacitive unbalance $C_{ub}\Delta x$ through which the capacitive crosstalk current i_C propagates from the disturbing pair into the disturbed

pair. This element also contains the inductive unbalance $M_{ub}\Delta x$, which causes the origination of inductive crosstalk voltage u_M in the disturbed pair. The sum of both crosstalk disturbances is the total crosstalk current i_x , which propagates along the disturbed pair to its near-end as a current i_N where it causes the near-end crosstalk, NEXT and another part propagates also to the far-end as a current i_F where it causes the far-end crosstalk, FEXT.

The crosstalk current i_{Cx} , which comes from the capacitive unbalance $C_{ub}\Delta x$, can be expressed [9]:

$$i_{Cx} = \frac{u_{Cx}}{\frac{1}{j\omega C_{ub}\Delta x} + \frac{Z_{C2}}{2}} \quad (1)$$

The term with Z_{C2} in the denominator can be neglected and the expression simplified:

$$i_{Cx} = j\omega C_{ub}\Delta x \cdot u_{Cx} \quad (2)$$

The voltage presented in the capacitive unbalance in the element Δx is given:

$$u_{Cx} = Z_{C1} \cdot i_1 \cdot e^{-\gamma_1 x} \quad (3)$$

and therefore the equation (1) can be expressed:

$$i_{Cx} = j\omega C_{ub}\Delta x \cdot Z_{C1} \cdot i_1 \cdot e^{-\gamma_1 x} \quad (4)$$

This current is divided; one part propagates to the near-end, while the second one to the far-end of the disturbed pair, as it is presented in [9], [15]. The difference between the FEXT current and the NEXT current is given by the positive/negative direction of the inductive unbalance current - i_{MF} . The current, which is caused by capacitive unbalance and appears at the far-end - i_{CF} , can be therefore calculated:

$$i_{CF} = \frac{1}{2} j\omega C_{ub}\Delta x \cdot Z_{C1} \cdot i_1 \cdot e^{-\gamma_1 x} \cdot e^{-\gamma_2(1-x)} \quad (5)$$

It is also possible to express the crosstalk voltage u_{Mx} , which comes from the inductive unbalance $M_{ub}\Delta x$ [9]:

$$u_{Mx} = j\omega M_{ub}\Delta x \cdot i_{Mx} = j\omega M_{ub}\Delta x \cdot i_1 \cdot e^{-\gamma_1 x} \quad (6)$$

Therefore the crosstalk current coming from the inductive unbalance and appearing at the far-end - i_{MF} can be calculated:

$$i_{MF} = -\frac{u_{Mx}}{2Z_{C2}} = -j\omega \frac{M_{ub}\Delta x}{2Z_{C2}} \cdot i_1 \cdot e^{-\gamma_1 x} \cdot e^{-\gamma_2(1-x)} \quad (7)$$

Based on the previous equations (5) and (7) it is possible to derive the summary far-end crosstalk current from both unbalances originating in the element Δx :

$$i_F = i_{CF} + i_{MF} = \frac{1}{2} j\omega \cdot i_1 \cdot e^{-\gamma x} \cdot e^{-\gamma_2(1-x)} \cdot \left(Z_{C1} C_{ub} \Delta x - \frac{M_{ub} \Delta x}{Z_{C2}} \right) \quad (8)$$

2.1 Standard Simple FEXT Model

To obtain the standard FEXT model, it is necessary to modify the equation (8) and to consider some simplifying assumptions, as described in [5]. Capacitive C_{ub} and inductive M_{ub} unbalances in a real metallic cable are generally varying along the cable, so they can be expressed as a function of their position x . But in case of the simplified standard FEXT model it is possible to assume both unbalances constant and equal to their mean values for the whole length of a cable l , so they are constant and independent on their positions x . Thanks to this assumption, it is possible to consider the element Δx as infinitely short and to express it by using differential term dx . Another simplification considers the transmission parameters of both pairs within the same cable to be identical (γ, Z_C).

According to these simplifications, the equation (8) can be modified:

$$i_F = j\omega \cdot Z_C \cdot i_1 \cdot e^{-\gamma x} \cdot e^{-\gamma(1-x)} \cdot \frac{1}{2} \left(\bar{C}_{ub} - \frac{\bar{M}_{ub}}{Z_C^2} \right) \quad (9)$$

The formula (9) can be further simplified:

$$i_{F_x} = j\omega \cdot u_1 \cdot e^{-\gamma l} \cdot \underbrace{\frac{1}{2} \left(\bar{C}_{ub} - \frac{\bar{M}_{ub}}{Z_C^2} \right)}_{\text{summaryunbalance}-C} = j\omega \cdot u_1 \cdot e^{-\gamma l} \cdot C \quad (10)$$

The FEXT crosstalk power transfer function is defined [14]:

$$|H_{FEXT}(f)|^2 = \frac{P_{FEXT}(f)}{P_I(f)} \quad (11)$$

In which $P_{FEXT}(f)$ represents the power function of far-end crosstalk and $P_I(f)$ the input power function at the near-end of a disturbing pair. The FEXT power transfer function can be obtained by an integration of crosstalk contributions (10) for the length l [8]:

$$P_{FEXT}(f) = |Z_C| \cdot i_F^2 = |Z_C| \cdot \omega^2 \cdot u_1^2(f) \cdot C^2 \cdot \int_0^l -e^{-2\gamma x} dx \quad (12)$$

Assuming electrically long symmetrical pairs [8] and (12) it is possible to express FEXT power transfer function (11) as:

$$|H_{FEXT}(f)|^2 = \frac{|Z_C| \cdot i_F^2}{|Z_C|} = \frac{|Z_C| \cdot \omega^2 \cdot u_1^2(f) \cdot C^2 \cdot l \cdot |H(f)|^2}{\frac{u_1^2(f)}{|Z_C|}}$$

$$|H_{FEXT}(f)|^2 = |Z_C|^2 \cdot \omega^2 \cdot C^2 \cdot l \cdot |H(f)|^2 \quad (13)$$

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

Where K_{FEXT} is a crosstalk parameter (a constant for the selected combination of pairs), which represents the summary rate of capacitive and inductive couplings between specific pairs. $|H(f)|^2$ is the power transfer function of a pair, f is the frequency and l represents the length of both pairs. Following the previous modifications, it is obvious, that [8]:

$$K_{FEXT} = |Z_C|^2 \cdot 4\pi^2 \cdot C^2 \quad (14)$$

Therefore K_{FEXT} crosstalk parameter is expressed through the integration of capacitive and inductive unbalances in (12). The equation (13) represents the standard simple FEXT model, which is presented in [5].

3. FEXT Model Based on Cascade Matrices and Capacitive Unbalances

The previously derived standard FEXT model uses several simplifications and assumptions. The most negative condition is the consideration of constant capacitive and inductive unbalances and their independence on the position x . However, for accurate and realistic FEXT modeling, it is necessary to assume varying unbalances along a cable. Nevertheless, analytical expression of these functions $C_{ub}(x)$, $M_{ub}(x)$, could be mathematically quite difficult. The values of these functions are probably varying pseudo-randomly in the interval given by manufacturing tolerances and other influences in a cable. It is possible to assume that the character of these functions would have probably the behavior of a normal distribution with the deviation given by these tolerances and imperfections of a cable. From this reason, it is not possible to use the operation of integration of the crosstalk contributions.

The main idea of this proposed FEXT model is dividing the whole cable into several transmission subsections with transmission lines, crosstalk coupling and the bridge taps from the unused ends of both symmetrical pairs. Each section is described by its cascade matrix and the final crosstalk current is calculated by their multiplication. First, several assumptions are necessary.

The model does not include the impact of a crosstalk through the third lines (circuits) in a cable, or an indirect effect of the crosstalk originating from reflections from the ends of the unused lines. Total crosstalk coupling is summararily expressed by its inductive and capacitive components, but the inductive part is approximated by the capacitive unbalance. This assumption is based on previous theoretical

considerations [10], according to which the impact of inductive coupling can be modeled by an additional capacitance unbalance and these two parts are included in the summary capacitive unbalance C' [11]. The last simplification of the model concerns the question of simulation and determination of the capacitive unbalance. It could be very complicated to express its values mathematically. Moreover, these values are usually pseudo-random and are influenced by many internal and/or external effects. That is why a simple method by generating pseudo-random values using formulas of normal distribution and the proper statistical values is used in the model. These assumptions will be further verified by comparing the results of simulations with the real characteristics of crosstalk measured for a cable with TCEPKPFLE specification.

Based on the previous assumptions it is possible to provide a schematic model of the whole situation, Fig. 2. Standard models for crosstalk between two pairs are usually based on the description of 4-port network, or two coupled 2-port networks, but for the basic crosstalk modeling, the simple 2-port model is sufficient.

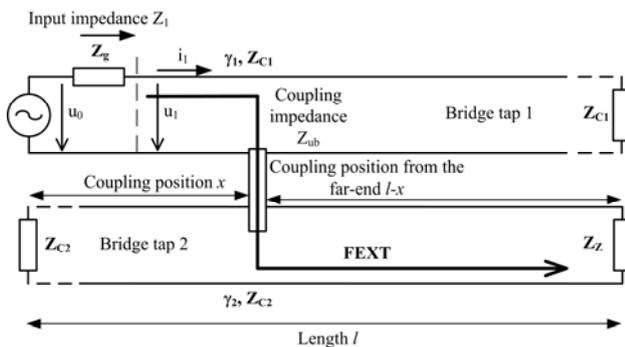


Fig. 2: The cascade elements of proposed FEXT model.

The signal generator with output voltage u_0 and internal impedance Z_g is located at the input of disturbing pair. The input impedance of the whole system Z_1 provides the total current i_1 and voltage u_1 . The summary capacitive coupling C' , which is represented by the impedance Z_{ub} , is situated in the position x from the beginning of a cable and $l-x$ from the far-end of a cable, while l is the length of a cable. This unbalance is situated in series with the generator from the perspective of FEXT crosstalk. The first bridge tap, which consists of the unused part of the disturbing pair and has length $l-x$, is connected to the unbalance in parallel. Also the unused section of the disturbed pair, which forms the second bridge tap of the length l , is connected in parallel. The rest of the disturbed pair with length $l-x$ is connected in series from the perspective of FEXT crosstalk. The far-end of the disturbed pair is terminated by the load impedance Z_Z . The propagation constant of disturbing pair is γ_1 and disturbed pair γ_2 . The ends of both bridge taps are opened, but the model could be further modified by terminating the taps by impedances Z_{C1} and Z_{C2} .

Now, it is possible to express the cascade matrices for the situation described in the Fig. 2 using previous formulas.

The cascade matrix of the transmission section of disturbing pair with the length x :

$$P_1 = \begin{pmatrix} \cosh(\gamma_1(f) \cdot x) & Z_{C1}(f) \cdot \sinh(\gamma_1(f) \cdot x) \\ \frac{\sinh(\gamma_1(f) \cdot x)}{Z_{C1}(f)} & \cosh(\gamma_1(f) \cdot x) \end{pmatrix}. \quad (15)$$

The cascade matrix of the first bridge tap, which consists of the unused section of disturbing pair with the length $l-x$:

$$O_1 = \begin{pmatrix} 1 & 0 \\ \frac{1}{Z_{C1}(f) \cdot \coth(\gamma_1(f) \cdot (l-x))} & 1 \end{pmatrix}. \quad (16)$$

The cascade matrix of the coupling impedance Z_{ub} :

$$V = \begin{pmatrix} 1 & Z_{ub} \\ 0 & 1 \end{pmatrix}. \quad (17)$$

In which the impedance Z_{ub} according to the previous assumptions can be calculated:

$$Z_{ub} = \frac{1}{j\omega C'}. \quad (18)$$

The cascade matrix of the second bridge tap, which represents the unused near-end of the disturbed pair with the length x :

$$O_2 = \begin{pmatrix} 1 & 0 \\ \frac{1}{Z_{C2}(f) \cdot \coth(\gamma_2(f) \cdot x)} & 1 \end{pmatrix}. \quad (19)$$

And finally, the cascade matrix of the rest transmission part of the disturbed pair, which is terminated by the impedance Z_Z at its far-end:

$$P_2 = \begin{pmatrix} \cosh(\gamma_2(f) \cdot (l-x)) & Z_{C2}(f) \cdot \sinh(\gamma_2(f) \cdot (l-x)) \\ \frac{\sinh(\gamma_2(f) \cdot (l-x))}{Z_{C2}(f)} & \cosh(\gamma_2(f) \cdot (l-x)) \end{pmatrix}. \quad (20)$$

The resulting cascade matrix W can be expressed by the multiplication of previous cascade matrices for all sections:

$$W = P_1 \cdot O_1 \cdot V \cdot O_2 \cdot P_2. \quad (21)$$

$$W = \begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix}.$$

The primary parameters can be calculated using British Telecom model and by using appropriate formulas, it is possible to obtain the characteristic impedances Z_{C1} , Z_{C2} and the propagation constants γ_1 and γ_2 . According to (14), it is possible to calculate summary capacitive unbalance from the crosstalk parameter K_{FEXT} . Based on the previous conclusions about the influence of

internal structure of a cable on resulting FEXT crosstalk [3], the K_{FEXT} parameter can be calculated for three main categories - the pairs within the same subgroup, pairs from two surrounding subgroups and pairs from two distant subgroups. The value of capacitive unbalance C' for each category can be therefore calculated using measured K_{FEXT} parameter and equation (22), which is based on (14):

$$C' = \sqrt{\frac{K_{FEXT}}{|Z_C|^2 \cdot 4\pi^2}}, [F / \sqrt{km; km, \Omega}]. \quad (22)$$

The far-end crosstalk current, which comes from one unbalance situated in the position x , can be calculated:

$$\begin{pmatrix} u_1 \\ i_1 \end{pmatrix} = \begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix} \cdot \begin{pmatrix} u_{Fx} \\ i_{Fx} \end{pmatrix}.$$

$$\frac{i_{Fx}(f)}{u_0(f)} = \frac{Z_g(f) + Z_z(f)}{Z_z(f) \cdot (Z_z(f) \cdot w_{11}(f) + w_{12}(f)) + \dots} \quad (23)$$

$$\dots \overline{Z_g(f) \cdot Z_z(f) \cdot w_{21}(f) + Z_g(f) \cdot w_{22}(f)}.$$

To calculate FEXT attenuation, it is necessary to summarize all contributions of crosstalk currents for the whole length l :

$$\frac{i_F(f)}{u_0(f)} = \sum_l \frac{i_{Fx}(f)}{u_0(f)}. \quad (24)$$

Therefore, the FEXT attenuation can be expressed:

$$A_{FEXT}(f) = 10 \cdot \log \frac{P_{1N}(f)}{P_{FEXT}(f)} [dB; W, W]. \quad (25)$$

With reference to (11), the equation (25) can be modified by expressing the power functions with voltages and proper impedances:

$$A_{FEXT}(f) = 10 \cdot \log \frac{P_{1N}(f)}{P_{FEXT}(f)} = 10 \cdot \log \frac{\frac{u_0^2(f)}{Z_{C1}(f)}}{\frac{u_F^2(f)}{Z_{C2}(f)}}. \quad (26)$$

Assuming the same characteristic impedances Z_c for both pairs in a cable ($Z_{c1}=Z_{c2}=Z_c$), it is possible to simplify (26) and to express the summary FEXT voltage $u_F(f)$ with (24):

$$A_{FEXT}(f) = 10 \cdot \log \frac{\frac{u_0^2(f)}{Z_{C1}(f)}}{\frac{u_F^2(f)}{Z_{C2}(f)}} = 20 \cdot \log \left| \frac{u_0(f)}{u_F(f)} \right|. \quad (27)$$

$$A_{FEXT}(f) = 20 \cdot \log \left| \frac{u_0(f)}{Z_z(f) \cdot u_0(f) \cdot \sum_l \frac{i_{Fx}(f)}{u_0(f)}} \right|.$$

Which finally leads into the expression of FEXT attenuation:

$$A_{FEXT}(f) = 20 \cdot \log \left| \frac{1}{Z_z(f) \cdot \sum_l \frac{i_{Fx}(f)}{u_0(f)}} \right| [dB]. \quad (28)$$

3.1 Results of Proposed Method of FEXT Modeling

The results obtained by presented method for FEXT crosstalk modeling are presented for metallic cable with the specification TCEPKPFLE 75x4x0.4 and length $l = 400$ m. The first step requires dividing the cable into several sub-sections with different crosstalk couplings. For that reason, the whole cable was divided into sections of 1 m each, which means 399 capacitive unbalances (400-1) for the whole cable with the of length 400 m. The crosstalk currents from all sections are then summarized. According to (22), it is possible to calculate summary capacitive unbalance from the crosstalk parameter K_{FEXT} . Based on the previous conclusions about the influence of internal structure of a cable on resulting FEXT crosstalk, the K_{FEXT} parameter can be calculated for three main categories - the pairs within the same subgroup, pairs from surrounding subgroups and pairs from distant subgroups. The value of capacitive unbalance C' for each category can be therefore calculated using measured K_{FEXT} parameter and equation (22). The K_{FEXT} parameter is usually derived for a cable with the length of 1000 m that's why it is necessary to provide recalculation for the situation of capacitive unbalance for sections - 1 m in this case, the formula comes from the expression of FEXT [8], [12]. The equation (22) could be hence modified to get the capacitive unbalance for the reference length of 1m:

$$C' [F / \sqrt{km}] = \frac{C' [F / \sqrt{km}]}{\sqrt{1000}} = \frac{\sqrt{\frac{K_{FEXT}}{|Z_C|^2 \cdot 4\pi^2}}}{\sqrt{1000}} = \quad (29)$$

$$= \sqrt{\frac{K_{FEXT}}{|Z_C|^2 \cdot 4\pi^2 \cdot 1000}}.$$

Tab.1: The calculation of capacitive unbalances.

The recalculation	K_{FEXT}	C' [F/m]
Pairs within the same subgroup	$9,9462 \cdot 10^{-17}$	$5,0194 \cdot 10^{-13}$
Pairs from surrounding subgroups	$1,292 \cdot 10^{-17}$	$1,8090 \cdot 10^{-13}$
Pairs from distant subgroups	$3,2040 \cdot 10^{-18}$	$9,0087 \cdot 10^{-14}$

As it was described before, the behavior of capacitive unbalance is varying along the cable in the interval of values with pseudo-random characteristic, which can be predicted using the formulas for normal distribution. Therefore, the values of capacitive unbalance C' in the Tab. 1 were subsequently used as a standard deviation for generating the character of capacitive unbalance $C'(x)$ with the zero mean value. The values of parameter K_{FEXT} were obtained from measured characteristics of TCEPKPFLE cable and by using statistical processing. Based on previous equations of proposed advanced FEXT model (21), (23), (24) and (28) together with the pseudo-randomly generated $C'(x)$ characteristic according to the values in Tab. 1, several examples of results were obtained. These results were compared with the measured characteristic of a cable and also with the standard FEXT model expressed by (13). The comparisons for different internal categories are presented in the following graphs Fig. 3, 4 and 5. All results are given for the frequency band from 12,9375 kHz to approx. 5,89 MHz.

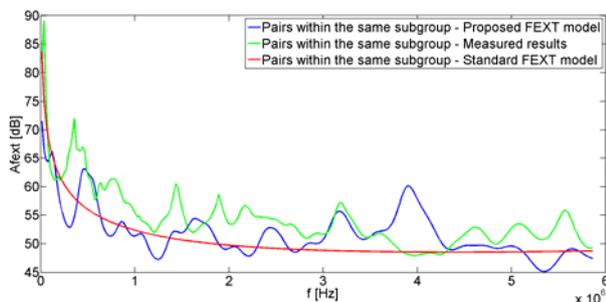


Fig. 3: The comparison of proposed FEXT model, standard FEXT model and measured results for pairs within the same subgroup.

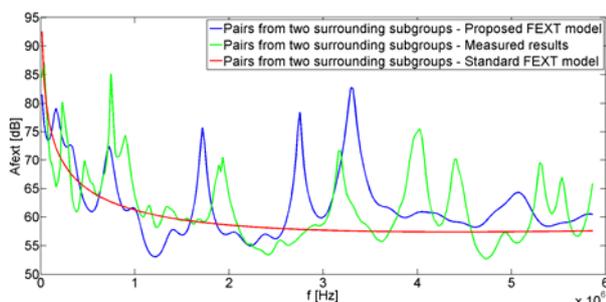


Fig. 4: The comparison of proposed FEXT model, standard FEXT model and measured results for pairs from two surrounding subgroups.

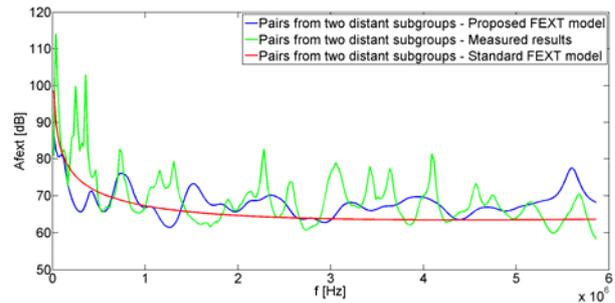


Fig. 5: The comparison of proposed FEXT model, standard FEXT model and measured results for pairs from two distant subgroups.

4. Conclusion

The equations from (15) to (29) were implemented into the simulation program in MATLAB environment. Based on the previous conclusions and measured results presented in chapter 2 for specific metallic cable of TCEPKPFLE type, the statistical parameters for generating the values C' capacitive unbalance for each constructional category. These values were subsequently used in the cascade matrices and equations of proposed FEXT model to obtain final results of simulations. Previous characteristics in the Fig. 3, 4 and 5 give an example of presented method of FEXT modeling, standard FEXT model and measured results for the frequency band to approx. 6 MHz. It is obvious that unlike the standard FEXT model (presented in the graphs as a red line), the proposed modeling method provides more accurate and realistic results. The standard model comes from only average values for the whole cable, the innovative method based on the varying function $C'(x)$ of both unbalances together with the influence of internal structure of the cable provides final results very close to the characteristics in real applications. The proposed model brings more accurate results and reaches realistic behavior of the transmission and crosstalk characteristics in a cable. The accuracy of the model could be further improved by more complex method of capacitive unbalance $C'(x)$ simulation and calculation as well as by respecting other influences in multi-pair and multi-quad metallic cables. The proposed model could also serve for the simulations and calculations of FEXT crosstalk and to prepare realistic results for implementing VDMT modulation into VDSL2 digital lines. The results of presented model were used in [16], [17] to estimate and calculate the transmission capacity of VDSL2 lines with VDMT modulation for FEXT cancellation.

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