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COMPENSATION OF CROSSTALK IN THE MULTI-BUNDLE DOMESTIC TELEPHONE CABLES

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КОМПЕНСАЦІЯ ПЕРЕХІДНИХ ЗАВАД У ВІТЧИЗНЯНИХ БАГАТОПУЧКОВИХ ТЕЛЕФОННИХ КАБЕЛЯХ

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КОМПЕНСАЦИЯ ПЕРЕХОДНЫХ ПОМЕХ В ОТЕЧЕСТВЕННЫХ МНОГОПУЧКОВЫХ ТЕЛЕФОННЫХ КАБЕЛЯХ

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Abstract. Mathematical models of the «vectoring» crosstalk compensation system for TPP-50x2 and TPP-100x2 multi-bundle telephone cables are developed. Simplified calculation formulas for the total power of the far end crosstalk and the crosstalk suppression by the «vectoring» system at parallel operation of xDSL-systems on the bundle twist cables with the number of bundles up to five are defined. Spectral power density level of the crosstalk ratio at the receiver's input of the transmission systems on VDSL2 technology without and with the «vectoring» system application is estimated depending on the signal frequency and the line length when TPP-50x2 and TPP-100x2 cables are fully loaded with the transmission systems. The efficiency of the «vectoring» crosstalk compensation system application is estimated by the crosstalk suppression value in the frequency range of up to 35 MHz with parallel operation of the VDSL2-systems on the domestic multi-bundle telephone cables TPP-50x2 and TPP-100x2 with up to 500 meters line length.

Key words: transmission system, crosstalk, power spectral density, «vectoring» system, multi-bundle telephone cable, crosstalk suppression.

Анотація. Розроблено математичні моделі системи компенсації перехідних завад «векторинг» для багатопучкових телефонних кабелів ТПП-50x2 та ТПП-100x2. Визначено спрощені формули розрахунку сумарної потужності перехідних завад на дальньому кінці та придушення системою «векторинг» перехідних завад при паралельній роботі СП xDSL по кабелях пучкового скручення з кількістю пучків до п'яти. Оцінено співвідношення рівня спектральної густини потужності перехідних завад на вході приймача систем передачі за технологією VDSL2 без та із застосуванням системи «векторинг» у залежності від частоти сигналу та довжини лінії при повному завантаженні кабелів ТПП-50x2 та 100x2 системами передачі. Оцінено ефективність застосування системи компенсації перехідних завад «векторинг» за величиною придушення перехідних завад у смузі частот до 35 МГц при паралельній роботі СП VDSL2 по вітчизняних багатопучкових телефонних кабелях ТПП-50x2 та 100x2 при довжині лінії до 500 м.

Ключові слова: система передачі, перехідні завади, спектральна густина потужності, система «векторинг», багатопучковий кабель, придушення завад.

Аннотация. Разработаны математические модели системы компенсации переходных помех «векторинг» для многопучковых телефонных кабелей ТПП-50x2 и ТПП-100x2. Определены упрощенные формулы расчета суммарной мощности переходных помех на дальнем конце и подавления системой «векторинг» переходных помех при параллельной работе СП xDSL по кабелям пучковой скрутки с количеством пучков до пяти. Оценено соотношение уровня спектральной плотности мощности переходных помех на входе приемника систем передачи по технологии VDSL2 без и с применением системы «векторинг» в зависимости от частоты сигнала и длины линии при полной загрузке кабелей ТПП-50x2 и 100x2 системами передачи. Оценена эффективность применения системы компенсации переходных помех «векторинг» по величине подавления переходных помех в полосе частот до 35 МГц при параллельной работе СП VDSL2 по отечественным многопучковым телефонным кабелям ТПП-50x2 и 100x2 при длине линии до 500 м.

Ключевые слова: система передачи, переходные помехи, спектральная плотность мощности, система «векторинг», многопучковый кабель, подавление помех.

The use of broadband access technologies (BA) by telephone network multipair cables still remains relevant. So the integration of ultra-high-bitrate xDSL technologies with optical broadband access technologies in hybrid BA networks based on FTTx concepts (for example FTTC+VDSL2 or FTTDp+G.fast) allows to compete successfully with fully optical networks based on FTTH concept.

FTTx+xDSL hybrid networks allow to provide a high-bitrate access to the terminal user (up to 1 Gbit/s with the G.fast technology application [1]) at significantly lower capital investments and the deployment time of BA network due to the use of existing telephone network cable infrastructure.

One of the main disadvantages of this variant of the BA network construction is a significant limitation of the transmission rate during the parallel operation of xDSL transmission systems (xDSL-systems) over telephone network multipair cables. Therefore, the success of ultra-high-bitrate xDSL-systems usage for the BA organization over telephone network depends on the successful solution of the crosstalk compensation problem, which is the main reason for the transmission rate limitation during the parallel operation over multipair cables. This problem was successfully solved by the crosstalk compensation system development, called «vectoring» [2].

It is known that TPP type cables are used on domestic telephone networks, the characteristics of which differ from the characteristics of foreign cables. Therefore the actual task is the development of appropriate mathematical models for the «vectoring» system usage during the operation over domestic multipair cables and the efficiency evaluation of its implementation.

The use of the «vectoring» has already been considered in works [3...5] for VDSL2 and G.fast systems when working over TPP-0,4 cable with bundle twist. TPP-0,4 is the most widespread on domestic telephone networks. The general analytical expression that determines the non-compensated crosstalk has been determined and which was simplified for cases of 10, 20 and 30-pair bundle twist cable on the condition that their own and transient attenuations are equal for all pairs of this cable, the averaged noises value calculation. However, this task was not solved in the specified works for telephone cables with a large number of pairs (with the number of bundles greater than 3).

The purpose of this article is mathematical model development of the «vectoring» crosstalk compensation system for TPP type multi-bundle telephone cables and the efficiency evaluation of the «vectoring» system usage during the xDSL-systems operation over the domestic multipair cables of TPP-50x2x0,4 and TPP-100x2x0,4 type.

A generalized block diagram and the algorithm of the «vectoring» system operation are considered in [3, 4].

As defined in [3], the general expression of far end crosstalk (FEXT) noise power without the «vectoring» $NFext_l$ at the transmission system № l (TS-l) receiver input by known signals S_m at the TS-m transmitter output is determined by:

$$NFext_l = \sum_{\substack{m=1 \\ m \neq l}}^{n} NFext_{l,m} = \sum_{\substack{m=1 \\ m \neq l}}^{n} S_m \cdot H_{l,m}\,, \tag{1}$$

where l, $m = 1, 2 \ldots n$; n – TS quantity; l – affected TS number; m – influencing TS number; $H_{l,m}$ – transient transfer function (TTF) between lines l and m; S_m – is the signal spectrum at the transmitter output of affecting TS.

The general expression of the non-compensated crosstalk $NFext^v{}_l$ generated by pre-distorted signals during the «vectoring» system application is determined by:

$$NFext^v{}_l = \sum_{\substack{m=1 \\ m \neq l}}^{n} \sum_{\substack{k=1 \\ k \neq m}}^{n} \frac{S_k \cdot H_{m,k}}{H_m} \cdot H_{l,m}\,, \tag{2}$$

where H_m is the own transfer function (OTF) of the line m.

The notion of a suppression coefficient was introduced for the efficiency evaluation of the «vectoring» system application, which in general was determined as follows:

$$KFext_l = \frac{NFext_l}{NFext^v{}_l} = \frac{\sum\limits_{\substack{m=1 \\ m \neq l}}^{n} S_m \cdot H_{l,m}}{\sum\limits_{\substack{m=1 \\ m \neq l}}^{n} \sum\limits_{\substack{k=1 \\ k \neq m}}^{n} \frac{S_k \cdot H_{m,k}}{H_m} \cdot H_{l,m}}\,. \tag{3}$$

In [5], simplified formulas for the crosstalk power calculation were determined from the general expressions (1) and (2) when working over TPP cables with bundle twist which have a small number of bundles (≤ 3), for the case when the xDSL systems have the same transmitters power $S = S_l$, and all lines in the multipair cable have the same OTF $H_l = H$, and TTF between the pairs inside the bundle is equal to $H_{l,m} = HFext^{\mathrm{I}}$, and between the pairs of adjacent bundle is equal to $H_{l,m} = HFext^{\mathrm{A}}$:

$$NFext_l = S\left[(x-1) \cdot HFext^I + (y+z) \cdot HFext^A\right], \tag{4}$$

$$\begin{aligned} NFext^v{}_l = \frac{S}{H} \cdot [&(x-1)^2 \cdot (HFext^I)^2 + (x \cdot y + x \cdot z + 2 \cdot y \cdot z) \cdot (HFext^A)^2 + \\ &+ (\mathrm{y}^2 + z^2 + x \cdot y + x \cdot z - 2 \cdot y - 2 \cdot z) \cdot HFext^I \cdot HFext^A], \end{aligned} \tag{5}$$

where x is the TS quantity in the 0th bundle, y is the TS quantity in the 1st bundle and z is the TS quantity in the 2nd bundle (for TPP-20x2 it is necessary to accept $z = 0$, and for TPP-10x2 it is necessary to accept y and $z = 0$); $HFext^I$ – TTF between pairs inside the bundle; $HFext^A$ – TTF between pairs of adjacent bundles.

The process for deriving an analytical expression for the crosstalk power calculation without and with the «vectoring» usage for multi-bundle cables is now discussed.

In TPP-50x2 cable, the pairs are divided into five bundles of 10 pairs. Each pair, in addition to crosstalk between pairs inside the bundle (expressed through $HFext^I$) and between pairs of adjacent bundles ($HFext^A$), the crosstalk between pairs, which are located through one bundle from the bundle in which the pair is a subjected to crosstalk ($HFext^{T1}$), must be taken into consideration. The total number of working TS (is equal to n) located in 50-pairs cable is in some way distributed between five bundles: $n = x + y + y' + z + z'$. In general case, each TS is subjected to the influence of $(x - 1)$ TS inside the bundle, $y + y'$ TS of two adjacent bundles and $z + z'$ TS of two bundles that are located through one bundle.

According to the above, formula (1) for the crosstalk power calculation without the «vectoring» usage $NFext_l$ at the input of the TS-l receiver takes the form:

$$NFext_l = S[(x-1) \cdot HFext^I + (y + y') \cdot HFext^A + (z + z') \cdot HFext^{T1}]. \tag{6}$$

The formula (2) for the non-compensated crosstalk power calculation $NFext^{v}{}_{l}$, generated by pre-distorted signals, takes the form:

$$\begin{aligned} NFext^{\mathrm{v}}{}_{l} = \frac{S}{H}[&(x-1)^2 \cdot (HFext^{I})^2 + (xy + yz + xy' + y'z') \cdot (HFext^{A})^2 + \\ &+(xz + y'z + xz' + yz') \cdot (HFext^{T1})^2 + \\ &+((x-1)\cdot(y+y') + y\cdot(y-1) + y'\cdot(y'-1)) \cdot HFext^{I} \cdot HFext^{A} + \\ &+((x-1)\cdot(z+z') + z\cdot(z-1) + z'\cdot(z'-1)) \cdot HFext^{I} \cdot HFext^{T1} + \\ &+(y\cdot(y'+z') + y'\cdot(y+z) + z\cdot(y+z') + z'\cdot(y'+z)) \cdot HFext^{A} \cdot HFext^{T1}]. \end{aligned} \tag{7}$$

Comparing the formulas (5) and (7) it can be concluded that with the increase of bundles in the multipair cable, the crosstalk definition when using the «vectoring» is considerably more complicated. Therefore, for the additional simplification of the expressions for the crosstalk calculation, we will continue to consider a separate case of the TS location in the cable, when the number of TS is the same in every bundle. In this case $x = n/n_b$, where n_b is the quantity of bundles in the cable, $x = y = y' = z = z'$ respectively. Then formulas (6) and (7) take the form:

$$NFext_l = S[(x-1)\cdot HFext^{I} + 2x\cdot HFext^{A} + 2x\cdot HFext^{T1}], \tag{8}$$

$$\begin{aligned} NFext^{v}{}_{l} = \frac{S}{H}[&(x-1)^2 \cdot (HFext^{I})^2 + 4x^2 \cdot (HFext^{A})^2 + \\ &+4x^2 \cdot (HFext^{T1})^2 + 4x\cdot(x-1)\cdot HFext^{I} \cdot HFext^{A} + \\ &+4x\cdot(x-1)\cdot HFext^{I} \cdot HFext^{T1} + 8x^2 \cdot HFext^{A} \cdot HFext^{T1}]. \end{aligned} \tag{9}$$

Formula (9) can be simplified and represented through (8) in the following form:

$$\begin{aligned} NFext^{\mathrm{v}}{}_{l} &= \frac{S[(x-1)\cdot HFext^{I} + 2x\cdot HFext^{A} + 2x\cdot HFext^{\mathrm{T}1}]^2}{H} = \\ &= \frac{(NFext_l)^2}{S\cdot H}. \end{aligned} \tag{10}$$

The expression (10) is also true for TPP-10x2, 20x2 and 30x2 cables. This is explained by the total symmetry of the crosstalk between the TS of all bundles in cables without dividing into the layers on the condition of the same TS quantity in every bundle. That is to say, $NFext_l$ of all pairs are the same. In this case, the formulas (8) and (10), respectively, can be written generally:

$$NFext_l = S[(x-1)\cdot HFext^{I} + x\cdot \sum_{k} HFext_k], \tag{11}$$

$$NFext^{\mathrm{v}}{}_{l} = \frac{(NFext_l)^2}{S\cdot H}, \tag{12}$$

where Σ – expresses the sum of crosstalk from the pairs of all other bundles; $HFext_k$, – TTF between pairs of k-th bundle and investigated pair.

Consequently, it is possible to calculate the total FEXT noise power without the crosstalk compensation system usage for the TSs, which operate over any TPP multipair cable with bundle twist by formula (11). It is possible to calculate the total non-compensated FEXT noise power with the application of the «vectoring» system for the TSs, which operate over TPP multipair cables with the number of bundles up to five by formula (12).

For the TPP-100x2cable, which consists of three bundles of the internal layer and seven bundles of the external layer, formula (12) is not true. In this case, the formula (11) for a pair located in any of the three bundles of the internal layer and the pair located in any of the seven bundles of the external layer accordingly takes the form:

$$NFext_{\mathrm{int}\,l} = S[(x-1)\cdot HFext^{I} + 2x\cdot HFext^{A} + 7x\cdot HFext^{AL}], \tag{13}$$

$$NFext_{ext\,l} = S[(x-1)\cdot HFext^{I} + 2x\cdot HFext^{A} + 2x\cdot HFext^{\mathrm{T1}} + \\ +2x\cdot HFext^{\mathrm{T2}} + 3x\cdot HFext^{AL}], \tag{14}$$

where $HFext^{AL}$ – TTF between pairs of bundles of adjacent layers; $HFext^{\mathrm{T2}}$ – TTF between pairs that are located through two bundles of one layer.

Now, formulas (13) and (14) allow to determine the expressions for the calculation of non-compensated crosstalk power $NFext^{v}{}_{l}$, but these expressions will be different for pairs in the bundles of internal and external layers. It is necessary to define the expression $NFext^{v}{}_{l}$ for the worst case, in which the total crosstalk power will be maximal – for pairs of the internal layer. For this variant, the (x-1) constituents of formula (13) are taken into consideration inside the bundle, 2x constituents of formula (13) from two adjacent bundles and 7x constituents of formula (14) from seven bundles of adjacent layer. As a result, we obtain:

$$NFext^{\mathrm{v}}{}_{\mathrm{int}\,l} = \frac{S}{H}[(x-1)^2\cdot(HFext^{I})^2 + 4x^2\cdot(HFext^{A})^2 + \\ +21x^2\cdot(HFext^{AL})^2 + 4x\cdot(x-1)\cdot HFext^{I}\cdot HFext^{A} + \\ +14x\cdot(x-1)\cdot HFext^{I}\cdot HFext^{AL} + 28x^2\cdot HFext^{A}\cdot HFext^{AL} + \\ +14x^2\cdot HFext^{T1}\cdot HFext^{AL} + 14x^2\cdot HFext^{T2}\cdot HFext^{AL}]. \tag{15}$$

Next, convert the resulting formulas into a view that is convenient for working with logarithmic values, taking into account that the parameters of the TS and cable are provided in logarithmic values (in dB, dBm/Hz, etc.). For this purpose, in the above formulas, it is necessary to use the signal spectral power density (SPD) instead of the signal power, instead of its OTF – the line attenuation and instead of the TTF – FEXT attenuation. Also, the fact that FEXT can be expressed through the far end crosstalk immunity (Equal Level Far End Crosstalk – ELFEXT) and line attenuation [6] needs to be considered:

$$A_{FEXT}(i) = A_{ELFEXT}(i) + \delta A_{ELFEXT}(i) + A_{line}(i), \tag{16}$$

where A_{FEXT} (i) – FEXT attenuation; A_{ELFEXT} (i) – immunity from the far end crosstalk between pairs inside the bundle; δA_{ELFEXT} (i) – ELFEXT increasing between pairs of different bundles (this value will be different for adjacent bundles $\delta A^{A}{}_{ELFEXT}$ (i), for bundles through one bundle $\delta A^{T1}{}_{ELFEXT}$ (i), for bundles through two bundles – $\delta A^{T2}{}_{ELFEXT}$ (i) and for bundles of adjacent layer – $\delta A^{AL}{}_{ELFEXT}$ (i)); A_{line} (i) – the line attenuation; i is the number of the xDSL-system carrier frequency.

As a result, formulas (8), (10), (13) and (15) respectively take the form:

$$Gnl50(i) = Gs(i) - A_{ELFEXT}(i) - A_{line}(i) + \\ +10\lg[(x-1) + 2x\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 2x\cdot 10^{-0,1\cdot\delta A^{T1}{}_{ELFEXT}(i)}], \tag{17}$$

$$Gnl^{v}50(i) = Gs(i) - 2\cdot A_{ELFEXT}(i) - A_{line}(i) + \\ +20\lg[(x-1) + 2x\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 2x\cdot 10^{-0,1\cdot\delta A^{T1}{}_{ELFEXT}(i)}], \tag{18}$$

$$Gnl100(i) = Gs(i) - A_{ELFEXT}(i) - A_{line}(i) + \\ +10\lg[(x-1) + 2x\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 7x\cdot 10^{-0,1\cdot\delta A^{AL}{}_{ELFEXT}(i)}], \tag{19}$$

$$\begin{aligned} Gnl^{v}100(i) = {} & Gs(i) - 2\cdot A_{ELFEXT}(i) - A_{line}(i) + \\ & +10\lg[(x-1)^2 + 4x^2\cdot 10^{-0,2\cdot\delta A^{A}{}_{ELFEXT}(i)} + 21x^2\cdot 10^{-0,2\cdot\delta A^{AL}{}_{ELFEXT}(i)} \\ & +4x\cdot(x-1)\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 14x\cdot(x-1)\cdot 10^{-0,1\cdot\delta A^{AL}{}_{ELFEXT}(i)} + \\ & +28x^2\cdot 10^{-0,1\cdot(\delta A^{A}{}_{ELFEXT}(i)+\delta A^{AL}{}_{ELFEXT}(i))} + 14x^2\cdot 10^{-0,1\cdot(\delta A^{T1}{}_{ELFEXT}(i)+\delta A^{AL}{}_{ELFEXT}(i))} + \\ & +14x^2\cdot 10^{-0,1\cdot(\delta A^{T2}{}_{ELFEXT}(i)+\delta A^{AL}{}_{ELFEXT}(i))}], \end{aligned} \tag{20}$$

where *Gnl*(*i*) – the PSD level of FEXT without the «vectoring» system usage; *Gs*(*i*) – the PSD level of the signal at the output of the transmitter; Gnlv(i) – the PSD level of FEXT with the «vectoring» system usage.

The «vectoring» system usage efficiency is convenient to express through the FEXT suppression (difference between PSD levels of FEXT without «vectoring» and with it) Δ*Gnl*(*i*), which is determined by the ELFEXT and the location of the TS in a multipair cable, regardless of the xDSL-system characteristics [5]. In accordance with (3), from formulas (17) ... (20) Δ*Gnl*(*i*) are determined as follows for TPP-50x2 and TPP-100x2:

$$\begin{aligned} \Delta Gnl50(i) = {} & Gnl50(i) - Gnl^{v}50(i) = \\ = {} & A_{ELFEXT}(i) - 10\lg[(x-1) + 2x\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 2x\cdot 10^{-0,1\cdot\delta A^{T1}{}_{ELFEXT}(i)}], \end{aligned} \tag{21}$$

$$\begin{aligned} \Delta Gnl100(i) = {} & Gnl100(i) - Gnl^{v}100(i) = \\ = {} & A_{ELFEXT}(i) - 10\lg[[(x-1)^2 + 4x^2\cdot 10^{-0,2\cdot\delta A^{A}{}_{ELFEXT}(i)} + 21x^2\cdot 10^{-0,2\cdot\delta A^{AL}{}_{ELFEXT}(i)} \\ & +4x\cdot(x-1)\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 14x\cdot(x-1)\cdot 10^{-0,1\cdot\delta A^{AL}{}_{ELFEXT}(i)} + \\ & +28x^2\cdot 10^{-0,1\cdot(\delta A^{A}{}_{ELFEXT}(i)+\delta A^{AL}{}_{ELFEXT}(i))} + 14x^2\cdot 10^{-0,1\cdot(\delta A^{T1}{}_{ELFEXT}(i)+\delta A^{AL}{}_{ELFEXT}(i))} + \\ & +14x^2\cdot 10^{-0,1\cdot(\delta A^{T2}{}_{ELFEXT}(i)+\delta A^{AL}{}_{ELFEXT}(i))}]/[(x-1) + 2x\cdot 10^{-0,1\cdot\delta A^{A}{}_{ELFEXT}(i)} + 7x\cdot 10^{-0,1\cdot\delta A^{AL}{}_{ELFEXT}(i)}]]. \end{aligned} \tag{22}$$

The evaluation will be carried out for a bandwidth of up to 35 MHz, it is used by the modern xDSL-systems (TS using VDSL2 technology [7]) for information transmission over the multi-bundle cables. The TPP cables parameters are determined from [6] and [8].

The frequency dependences of the PSD level of the total FEXT noise power are calculated by (17)...(20) at 100 % loading of the multipair cables TPP-50x2x0,4 and TPP-100x2x0,4 by VDSL2-technology transmission systems at different lengths of the subscriber line are shown in Fig. 1 and 2. For comparison, in figures «–140 AWGN» noise level is also indicated (it has minus 140 dBm/Hz PSD level), which corresponds to the absence of external additive noises and is determined by the maximum power of thermal noises. The results of FEXT suppression calculated by (21) and (22) are shown in Fig. 3.

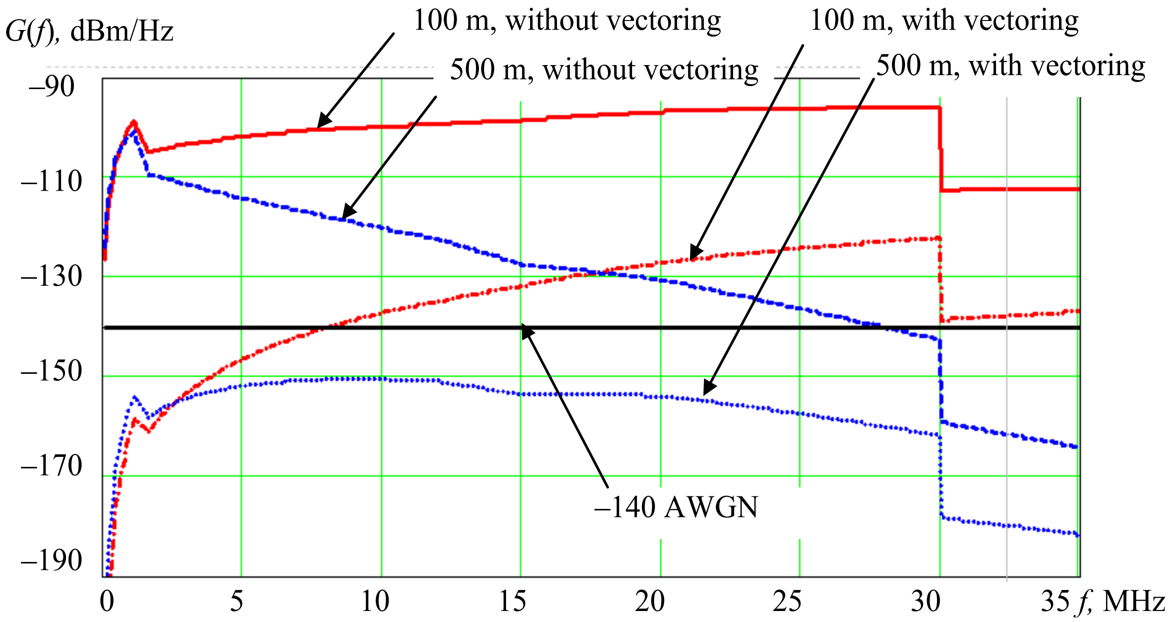

Figure 1 – Frequency dependence of the PSD level of the total FEXT noise power at 100% loading of the TPP-50x2x0,4 cable by VDSL2-systems

Analyzing the results, we can reach the following conclusions:

– in case of TS operation without the «vectoring» system application, FEXT considerably exceed the level of minus 140 dBm/Hz, so they will determine the total SNR and achievable transmission rate of xDSL-systems;

– the «vectoring» application allows to reduce significantly the FEXT level: according to Fig. 3 depending on the line length and the signal frequency the FEXT suppression for cable TPP-50x2 is 15.4...61 dB, and for TPP-100x2 – 13.9...60 dB, the use of the «vectoring» system leads to the fact that for the VDSL2-system in the band of up to 7 MHz for 100 meters line length, the FEXT level does not exceed the thermal noise level (minus 140 dBm/Hz), and the maximum FEXT level does not exceed minus 120 dBm/Hz (see Fig. 1 and 2).

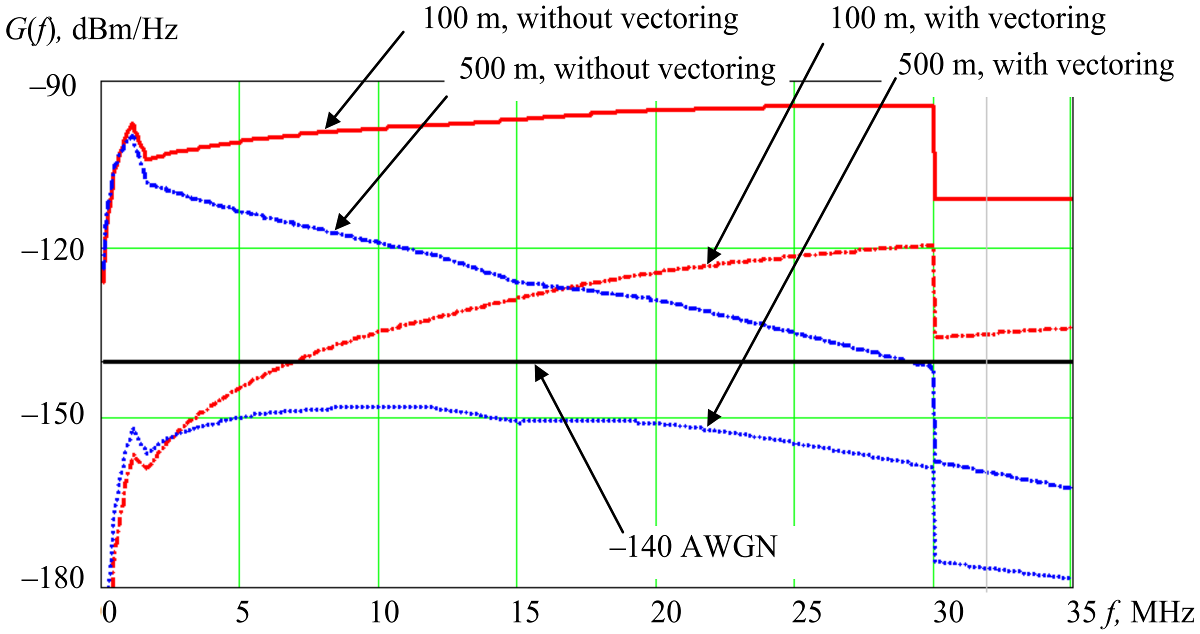

Figure 2 – Frequency dependence of the PSD level of the total FEXT noise power at 100% loading of the TPP-100x2x0,4 cable by VDSL2-systems

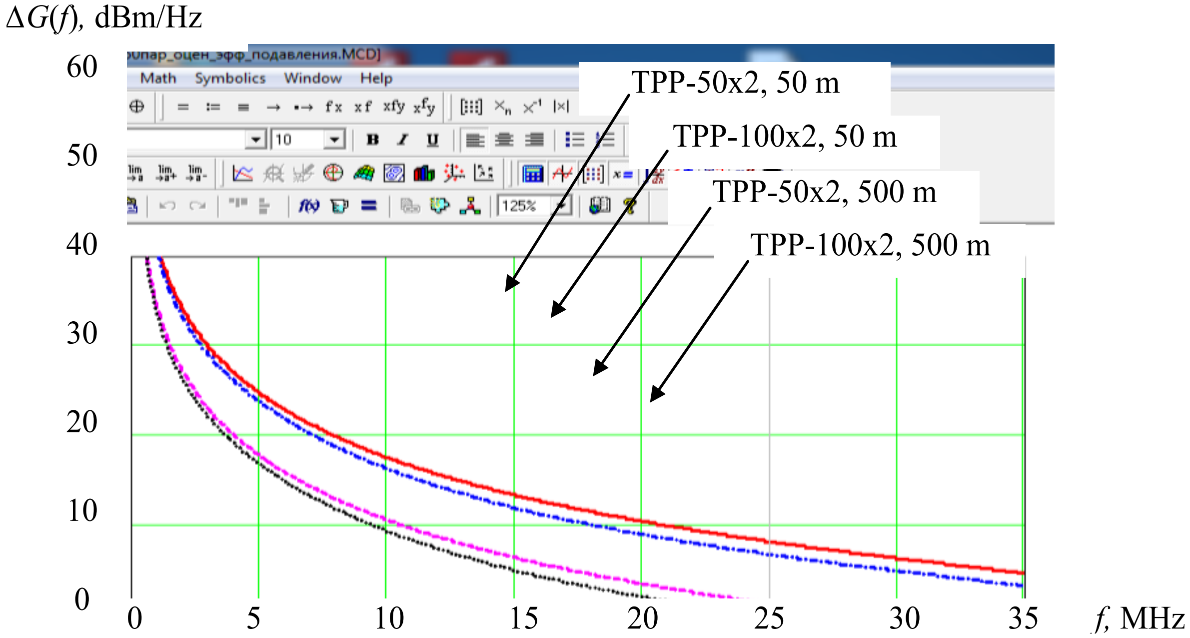

Figure 3 – Frequency dependence of FEXT suppression with 50 and 500 meters line length and 100% loading of the TPP cables by transmission systems

Conclusion.

Mathematical models of the «vectoring» crosstalk compensation system for domestic TPP-50x2 and TPP-100x2 multi-bundle cables were developed.

The efficiency estimation of the «vectoring» system application during the operation of the xDSL-system over the domestic TPP-50x2 and TPP-100x2 multipair telephone cables is given. FEXT suppression at 100% loading of the TPP cables by transmission systems, depending on the line characteristics can reach 61 dB, and the FEXT level does not exceed minus 120 dBm/Hz.

The research shows that the «vectoring» system application in xDSL-systems operating over multi-bundle telephone cables effectively counteract crosstalk, suppressing them to the thermal noise level.

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