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Using Advanced Far-end Crosstalk Modeling Method for Simulations of Very High Speed Digital Lines

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Introduction

The new generation of Very High Speed Digital Subscriber Lines (VDSL2) could perspectively offer transmission rate of tens of Mbps in both directions [1]. However, the crosstalk and other disturbances in metallic cables represent the main problem for achieving this transmission rate. While the influence of near-end (NEXT) crosstalk can be partially limited by using several different frequency bands for both directions (there are several various frequency plans, scenarios, for VDSL2 lines), the influence of far-end crosstalk (FEXT) cannot be reduced so easily. Therefore FEXT represents the dominant source of disturbance in current digital transmission systems, such as xDSL (VDSL2) lines [2]. FEXT crosstalk is caused by capacitive and inductive unbalances between symmetrical pairs in a cable, because these pairs, although constructed symmetrically, always perform minor electrical and constructional unbalances towards themselves [3].

The elimination of FEXT crosstalk could be possibly provided by Vectored DMT modulation (VDMT). This modulation is an upgrade of previous Discrete Multitone modulation (DMT) and it is based on the perfect synchronization of transmitted DMT symbols and the knowledge of transmission functions for all symmetrical pairs in a cable and transmission functions of FEXT crosstalk between all combinations of disturbing and disturbed pairs. Based on these FEXT transmission functions a coordination of transmitted DMT symbols could be performed and thus reduce the FEXT crosstalk between them [4]. However, the metallic cables used for access telecommunication networks usually contain hundreds of symmetrical pairs (it means thousands of mutual combinations), which makes the coordination of transmitted symbols very difficult, because the whole process is mathematically very demanding. One of the possibilities how to simplify the whole process would be accurate and realistic simulations and estimations of FEXT crosstalk based on simple method of generating pseudorandom characteristics using measured parameters of a cable. However, this method would require very accurate prediction of crosstalk behavior and realistic modeling of FEXT for all mutual combinations of pairs in a cable. That is why a new advanced method of FEXT modeling is necessary to implement.

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. The main idea is to implement 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 greatly improve the accuracy of a model and should provide more realistic results. Although the model was derived from measurements performed on UTP cable, it could be used for any metallic cable with symmetrical pairs or quads with some minor revisions of proposed constants in its formula.

The next part of this paper is focused on the application of derived model and present the simulation of VDSL2 lines. These simulations and calculations of a summary transmission rate are based on the results of the advanced FEXT model together with the VDMT modulation for the elimination of crosstalk.

Standard FEXT model, ITU-T FEXT model

The standard model of FEXT crosstalk between twisted pairs or quads in a cable comes from the derivation of interactions between them, which results in the formula [5] given as

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

where $|H_{FEXT}(f)|^2$ represents the power transfer function of FEXT between two pairs, $|H(f)|^2$ is the power transfer function of a pair, l is a length of pairs, f is a frequency and

K_{FEXT} is a crosstalk parameter. This parameter presents the rate of crosstalk between selected pairs and it is generally unique for each combinations. 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 [6], 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 [6], as

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

where $|H_{FEXT}(f,d)|$ stands for a FEXT voltage transfer function for frequency f in Hz and FEXT coupling length d in m. $XT_k(i)$ in dB represents the FEXT sample at $f=f_{FXT}$ and $d=d_{FXT}$, γ is a propagation constant of a line and $\phi_k(i)$ in rad/m is a uniformly distributed random variable over [0, 2π]. Although the model uses randomly distributed variable, it still does not provide very realistic and accurate results.

The results accuracy of both models can be sufficient for some specific applications (summarization of many contributions), but these simple models are not very useful for the precise and realistic modeling of perspective VDSL2 lines. 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.

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 using Rohde&Schwarz Vector Network Analyzer 10Hz/9kHz, 4GHz-ZVRE, in a frequency band from 100kHz to 100MHz. North Hill's balun transformers with impedance ratio 50/100Ω were used for proper termination and coupling of a cable. The original length of a cable was 264.5m and after measuring the attenuation of all pairs and FEXT attenuation between all combinations of pairs (4 attenuations, 6 FEXT attenuations), 1m of a cable was cut and the measurements were performed again. In this way with the step of 1m, the measurements were repeated until the cable was only 15.5m long. Because FEXT depends on a length of a cable it was necessary to perform its recalculation for a unified length according to a formula (3) to be able to compare FEXT characteristics for different length, which can be expressed according to [7] as

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

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

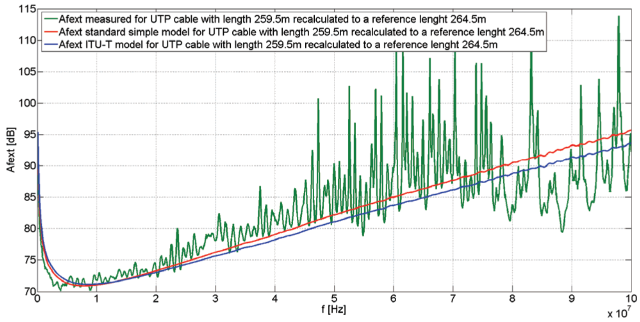

Fig. 1. Measured FEXT attenuation, simple FEXT model and ITU-T model for a UTP cable with length 259.5 m recalculated to a ref. length 264.5 m

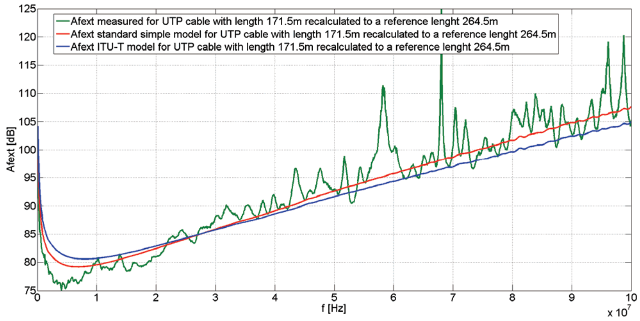

Fig. 2. Measured FEXT attenuation, simple FEXT model and ITU-T model for a UTP cable with length 171.5 m recalculated to a ref. length 264.5 m

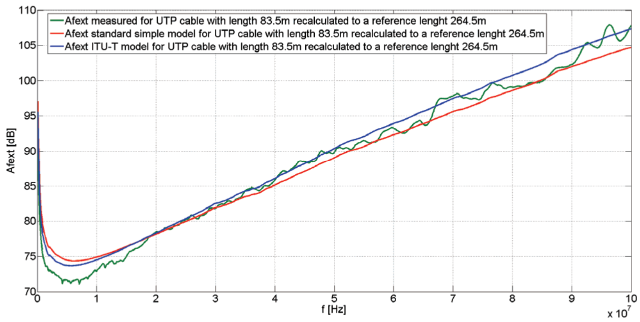

Fig. 3. Measured FEXT attenuation, simple FEXT model and ITU-T model for a UTP cable with length 83.5 m recalculated to a ref. length 264.5 m

From characteristics in above figures is evident that the simple standard FEXT model and ITU-T model provides 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 cable length l and the wavelength λ of a propagating signal. While for the cable length 259.5m the FEXT characteristic has plenty sharp peaks and dips, the same FEXT characteristic for the cable length 171.5m is smoother (the peaks and dips are not so intensive) and the FEXT characteristic for the cable length 83.5m 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 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 cable length l and wavelength λ of a propagating signal is evident. There are several effects influencing the transmission parameters of symmetrical pairs on high frequencies, such as skin effect, or effect of proximity to the surrounding symmetrical pairs, which are more dominant for shorter lengths. However, the main conclusion is that the period of frequency dips and peaks depends on the ratio given by the cable length and the wavelength of a propagating signal. This is caused by the presence of capacitive and inductive unbalances in the cable (these unbalances are the source of crosstalk) and it depends on the phase and amplitude of the propagating electromagnetic signal, in which this signal reaches this unbalance.

The wavelength $\lambda(f)$ of propagating signal could be calculated using the light velocity in a vacuum c (299792458m/s), frequency f and ε_r, which is a relative permittivity of material used for insulation in a cable [3] as

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

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 to implement cosine harmonic functions (either sine or cosine could be used) with arguments equal to the ratio given by the cable length l and the wavelength of a propagating signal λ. To maintain the mean value of both cosines close to zero, one of them must be positive and the other negative but with the same amplitude. While the amplitude of a cosine is 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 it is necessary to use the absolute value.

The resulting advanced FEXT model with all previous conclusions and mathematical notation could be expressed as:

$$\begin{cases} |H_{FEXT}(f)|^2 = \left| K_{FEXT} \cdot l \cdot f^2 \cdot |H(f)|^2 + \right. \\ \qquad \left. + K_{NORM} \cdot \left(\cos\frac{2\pi l}{5\lambda} - \cos\frac{9\pi l}{10\lambda} \right) \right|, \\ A_{FEXT}(f) = -10\log\left[\left| K_{FEXT} \cdot l \cdot f^2 \cdot |H(f)|^2 + \right.\right. \\ \qquad \left.\left. + \frac{3}{40 \cdot l^3} \cdot \left(\cos\frac{2\pi l}{5\lambda} - \cos\frac{9\pi l}{10\lambda} \right) \right| \right]. \end{cases} \tag{5}$$

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 and 5.

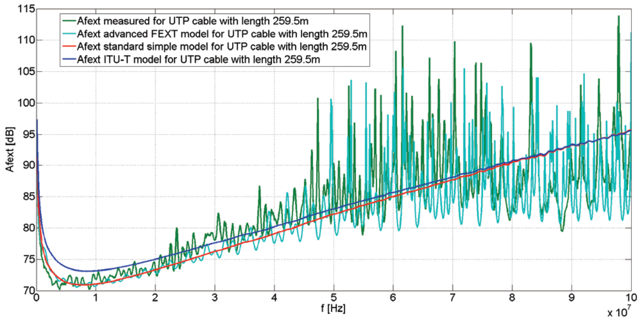

Fig. 4. The comparison between measured results, models and the advanced FEXT model for the length of a cable 259.5 m

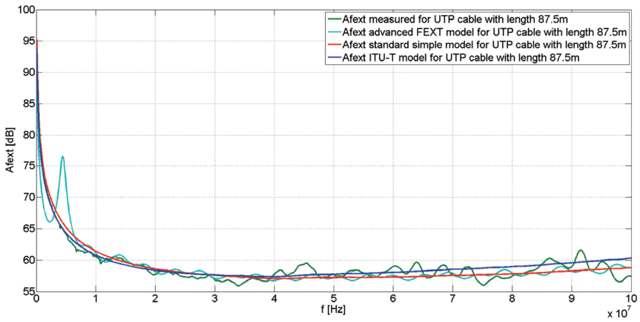

Fig. 5. The comparison between measured results, models and the advanced FEXT model for the length of a cable 87.5 m

The proposed FEXT model was also verified for metallic cables with various internal structures, core diameters and lengths. The example of results for cable PEPKFH 30x2x0.5 with the length of 502m is presented in Fig. 6. The value of K_{NORM} constant in (5) is valid for a UTP cable, therefore it is necessary to provide its derivation for PEPKFH cable. Its value depends on the twisting ratio, core diameter, propagation constant and for PEPKFH cable, the value of K_{NORM} was calculated experimentally with use of using measured characteristics.

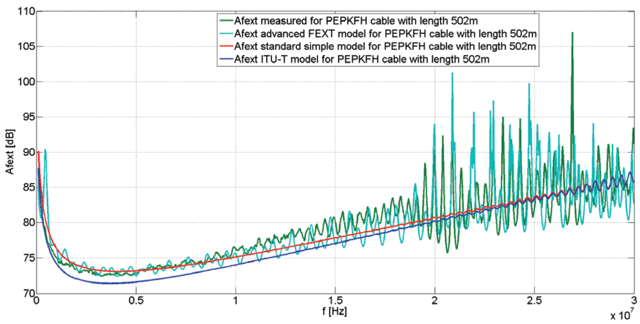

Fig. 6. The advanced FEXT model, both standard models and measured characteristic for PEPKFH cable

Other verifications of proposed advanced FEXT model were performed for two metallic cables with different core diameter. Both cables - SYKFY 4x2x0.5 and F-02YHQ2Y 4x2x0.6 are very often used for local networks or access networks. The SYKFY 4x2x0.5 cable was 102m long and F-02YHQ2Y 4x2x0.6 cable was also

10m long. The values of K_{NORM} constants for both cables in (5) were calculated individually. The results of the advanced FEXT model, standard FEXT model, ITU-T model and measured characteristics in Fig. 7 are presented for SYKFY cable and in Fig. 8 for F-02YHQ2Y cable.

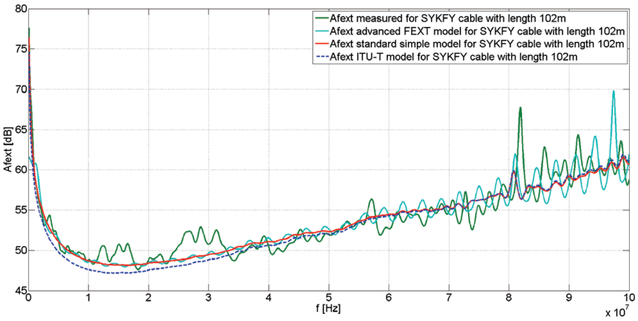

Fig. 7. The advanced FEXT model, both standard models and measured characteristic for SYKFY cable

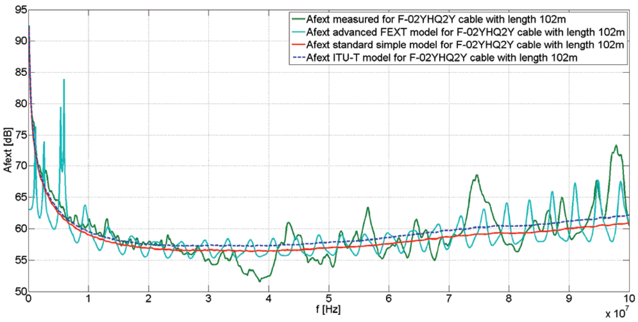

Fig. 8. The advanced FEXT model, both standard models and measured characteristic for F-02YHQ2Y cable

Transmission performance modeling of lines with VDMT modulation

It was mentioned that the FEXT crosstalk affects the total transmission performance of VDSL2 line. Therefore, to perform precise transmission simulations is necessary to use the advanced FEXT level calculation method, as described in this paper.

VDMT modulation is extension of the classical DMT modulation and it is designed exactly for the purpose of FEXT crosstalk attenuation. The principle of modulation VDMT lays in idea to adjust a transmitted signal so that after it will go through a subscriber line, where it is influenced by a crosstalk disturbance and the cable attenuation characteristic, it could be detected on a reception side without any serious problems.

To carry out a coordination of each DMT symbol (which represents transmitted user data) for all user lines and for all tones [2], it would require a use of very demanding computational process.

The classic method for calculating a transmission performance is based on the summarization of the total disturbance in the line, determination of a signal to noise ratio and estimation of the transmission rate. Interference is expected only from the system in the same class (in terms of spectral compatibility). For a crosstalk simulation usually a common model that is being use is consortium FSAN (Full Service Access Network) model [8].

The other method of modeling the transmission performance for the purposes of theoretical simulation, determines the reduction of crosstalk disturbance with repeating calculation of the crosstalk parameter K_{FEXT} [9].

Utilization of realistic FEXT model for transmission performance simulation

The simulation program Simulator xDSL is designed to perform calculations within the spectral compatibility sphere in a metallic access network and calculations concerning a transmission performance for several types of digital subscriber lines.

The program was created in the MATLAB® environment of The MathWorks, Inc. corporation. Program input parameters are a type and a subscriber loop topology, a transmission environment type and a xDSL system type.

According to the set of input parameters, the program is able to calculate the value of the theoretical transmission performance of an xDSL line.

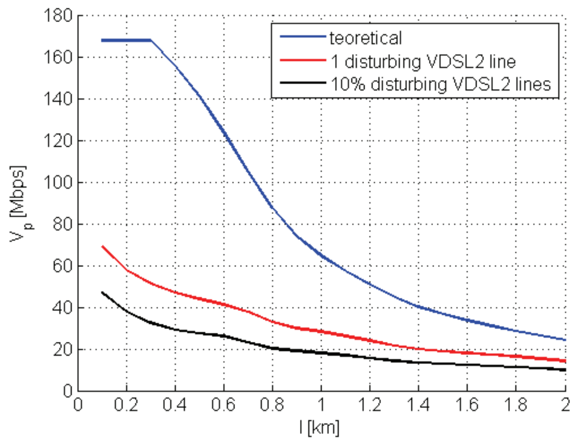

Fig. 9. Transmission rate VDSL2 line, frequency band plan B8-12 for downstream direction

Fig. 9 shows graphical results of a dependency of the maximal available transmission rate (17MHz, B8-12) on the line length and number of the disturbing systems. A local subscriber loop is made from a symmetrical pair of the Cu metallic telecommunication cable with 75 star quad elements and diametr 0.4mm (TCEPKPFLE 75x4x0.4mm). The subscriber loop length starts at 0.1km, ends at 2km, with the step of 0.1km.

The second output from program is one of possible realizations of the crosstalk disturbance signal in the time domain (shown in Fig. 10). This signal can be store and use in the future for difference purposes.

The third output is calculated from the transmission parameters of the defined loop topology (subscriber loop attenuation, impulse response, etc.).

The simulation program allows to perform simulation of all lines xDSL types, from HDSL, SDHSL, ADSL, ADSL2+ to VDSL2. For each transmission technology it is possible to set up an additional parameter. For example, for ADSL it is necessary to set up a method for duplex transmission (a frequency division or an echo cancelation). The transmission environment is modeled with use of the noise profiles A, B, C, D, defined by ITU-T for each technology. However, it is also possible to use one's own combination of different transmission technologies. The simulation program uses the 13 parametric British Telecom model for the local loop modeling. The PSD calculations (crosstalk or the signals of interest) are under ITU-T recommendations.

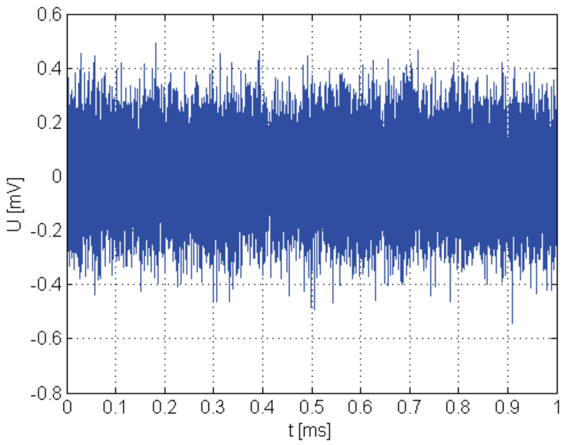

Fig. 10. An example of the second output from program

Advanced far-end crosstalk modeling method and method for modeling the transmission performance using modulation VDMT are implemented in the simulation program Simulator xDSL.

Table 1 shows the values of VDSL2 line transmission performance. The values of transmission performance are set depending on the number of coordinated lines. All VDSL2 lines use a frequency plan B8-12 for Europe up to 17MHz (998ADE17).

This frequency plan allows, of course theoretically, to achieve transmission rate above 100Mbps. A local subscriber loop is made from a symmetrical (twisted) pair of the Cu metallic cable CAT5e. The subscriber loop length is 264.5m. The theoretical transmission performances values are calculated based on the full coordination of disturbing sources, from no coordinated systems to full coordination of all 3 disturbing sources of the same class.

Table 1. VDSL2 line transmission performance

Coord. lines	Direction	Pair transmission rate [Mbps]			
		1	2	3	4
0	Upstr.	43.9	47.2	44.5	44.6
	Downstr.	109.0	116.6	110.5	110.7
1	Upstr.	46.3	49.6	47.4	47.6
	Downstr.	114.7	122.1	116.9	117.8
2	Upstr.	54.7	54.6	50.2	50.9
	Downstr.	132.5	133	123.8	125
3	Upstr.	70.6	70.6	70.6	70.6
	Downstr.	165.0	166	165.9	167.6

Depending on the frequency plan, VDSL2 line can achieve transmission rate of tens Mbps. CAT5 cable transmission environment allows parallel operation of multiple VDSL2 lines. If the inverse multiplexing is used, it is possible to achieve approximately 440Mbps in downstream direction (loop length 264.5m, frequency plan 998ADE17). With use of modulation VDMT, it is possible to achieve theoretically up to 660Mbps.

Transmission environment of the copper cables for LAN can be used to transmit signals VDSL2 connections. With VDSL2 lines is possible to attain an acceptable transmission performance, but at significantly greater distances than traditional systems such as the 100/1000BASE-T.

Conclusions

In this paper a new method for simulating and modeling of FEXT transmission functions in real metallic cables was proposed and presented. This new model provides above mentioned more accurate and realistic results of FEXT characteristics. The results of the model were verified for various metallic cables with symmetrical pairs or quads with some minor revisions of proposed constant in formula (5). This new accurate model could serve for realistic simulations and calculations of FEXT and for preparing realistic results with implementing VDMT modulation into VDSL2 digital lines, as it was also presented in this paper.

Acknowledgements

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Digital subscriber lines are designed for efficient use in today's fixed access networks, which are made of symmetrical copper pairs. These lines allow to realize high-speed data transfers. The transmission performance of these connections is highly dependent on conditions of the real transmission environment. The main parameters affecting the transmission performance are the line attenuation and crosstalk noise. Considering that it is not possible to perform tests in real network access, because there were influencing data streams of end users, it is necessary to carry out all tests in the experimental access networks. Due to the cost of building such a experimental network, all the tests are carried out as simulations. For simulations it is necessary to accurately model the real conditions of transmission access network. The article describes methods for accurate modeling of the far end crosstalk, which is dominant for digital subscriber line. The second part of the article describes the crosstalk model used for calculating transmission performance of digital subscriber transmission line that uses vectored discrete multitone modulation to transfer user information. They are given specific values of the theoretical efficiency of transmission, depending on various conditions of transmission. Ill. 10, bibl. 8, tabl. 1 (in English; abstracts in English and Lithuanian).

P. Jares, P. Lafata. Didelės spartos skaitmeninių linijų modeliavimas naudojant sankirtų trukdžių modeliavimo metodą // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 5(121). – P. 41–46.

Skaitmeninėmis perdavimo linijomis duomenis galima perduoti didele sparta. Šių sujungimų perdavimo našumas labai priklauso nuo realių perdavimo linijos aplinkos sąlygų. Pagrindiniai parametrai, lemiantys perdavimo našumą, yra linijos slopinimas ir sankirtų trukdžiai. Todėl neįmanoma atlikti testų realiai veikiančiame tinkle, nes jis yra veikiamas vartotojų duomenų srautų, taigi eksperimentus reikėtų atlikti eksperimentiniame tinkle. Tam reikia daug lėšų, todėl visi testai buvo atlikti modeliuojant. Pateikiami metodai skirti sankirtų trukdžiams tiksliai modeliuoti. Pateikiamos teorinės perdavimo efektyvumo vertės, priklausančios nuo įvairių sąlygų. Il. 10, bibl. 8, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).