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EFFICIENCY OF TELECOMMUNICATION SYSTEMS TRANSMISSION OF FIXED BROADBAND ACCESS THROUGH TELEPHONE CABLES

В. Балашов, В. Орєшков, І. Барба, І. Макаров. **Ефективність телекомунікаційних систем передачі фіксованого широкосмугового доступу по телефонним кабелям.** У статті наведено оцінку ефективності систем передачі інформації цифровими абонентськими лініями фіксованого широкосмугового доступу по багатопарних телефонних кабелях з використанням системи компенсації перехідних завад «векторинг» між системами передачі. Запропоновано методику розрахунку відношення сигнал/шум на вході приймача, яка враховує частотні характеристики та адитивні завади ліній, не скомпенсовані перехідні завади між системами передачі, що взаємовпливають, і обмеження потужності переданих сигналів, пов'язане з нормуванням потужності передавача, викликане використання системи «векторинг». Ефективність систем передачі за допомогою системи компенсації перехідних перешкод «векторинг» оцінені моделі мережі широкосмугового доступу за технологією G.fast при застосуванні багатопарного телефонного кабелю типу ТПП з кількістю пар до 100 в діапазоні частот до 106 МГц і довжинах лінії до 250 метрів. Оцінено досяжну швидкість передачі в залежності від характеристик абонентських ліній, числа паралельно працюючих систем передачі та обмеження потужності переданих сигналів. Визначено, що основною причиною обмеження досяжної швидкості передачі інформації при використанні системи «векторинг» є частотні характеристики та адитивні завадии абонентських ліній, не скомпенсовані перехідні завадии та обмеження потужності сигналу, що передається. Запропонована методика оцінки відношення сигнал/шум та досяжної швидкості передачі інформації з системами компенсації перехідних завад «векторинг» може бути застосована в задачах проектування та побудови мереж фіксованого широкосмугового доступу, що використовують як середовище передачі багатопарні телефонні кабелі та кабелі типу «вита пара».
Ключові слова: широкосмуговий доступ, система передачі, швидкість передачі, телефонний кабель, «вита пара», перехідні завади, спектральна густина потужності, відношення сигнал/шум, алгоритм (система) «векторинг»

V. Balashov, V. Oreshkov, I. Barba, I. Makarov. **Efficiency of telecommunication systems transmission of fixed broadband access through telephone cables**. The article provides an assessment of the efficiency of transmission data systems by digital subscriber lines of fixed broadband access over multi-pair telephone cables using the transient interference compensation system "vectoring" between transmission systems. A technique for calculating the signal-to-noise ratio at the receiver input is proposed, which takes into account frequency characteristics and additive interference of lines, uncompensated transient interference between mutually influencing transmission systems, and the limitation of the power of transmitted signals associated with the normalization of the transmitter power, caused by the use of the "vectoring" system. The effectiveness of transmission systems with the help of the transient interference compensation system "vectoring" is evaluated by broadband access network models using G.fast technology when using a multi-pair telephone cable of the TPP type with the number of pairs up to 100 in the frequency range up to 106 MHz and line lengths up to 250 meters. The achievable transmission speed is estimated depending on the characteristics of subscriber lines, the number of parallel operating transmission systems and the limitation of the transmitted signal power. It was determined that the main reason for limiting the achievable speed of information transmission when using the "vectoring" system is the frequency characteristics and additive interference of subscriber lines, uncompensated transient interference and limitation of the power of the transmitted signal. The proposed method of evaluating the signal/noise ratio and the achievable speed of data transmission with vectoring transient interference compensation systems can be applied in the tasks of designing and building fixed broadband access networks that use multi-pair telephone cables and twisted pair cables as a transmission medium.
Keywords: broadband access, transmission system, transmission speed, telephone cable, «twisted pair», transient disturbances, power spectral density, signal/noise ratio, algorithm (system) "vectoring"

1. Introduction

To build fixed broadband access (FBA) networks to the Internet, both optical cables and transmission data systems (TDS) and multi-pair telephone cables, twisted pair cables and TDS using xDSL

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technology (TDS xDSL) are widely used [1]. The most effective TDS xDSL using G.fast technology (G.fast IPS) provide transmission speeds over broadband networks up to 1 Gbit/s and higher [2, 3].

2. Analysis of literature data and problem statement

TDS xDSL technologies are constantly being improved and developed. The latest update to Recommendation G.9700 (G.fast) dates back to March 2019 [3]. MGfast TDSs have already been developed and standardized, which provide multi-gigabit transmission speeds over multi-pair cables [4, 5]. The development of xDSL technologies is moving along the path of increasing transmission data speeds over a broadband access network to terabits [6, 7].

The limitation of the transmission speed of TDS xDSL over transmission lines of a broadband access network is caused, along with additive white noise and the inherent attenuation of transmission lines, also by transient interference (TI) between TDS operating over a common transmission medium – multi – pair cables.

The high speed of data transmission of TDS xDSL when working over a common transmission medium is ensured through the use of an TI compensation system called “vectoring” [8, 9]. The “vectoring” algorithm includes measuring the TI from the TDS operating over a common transmission medium and introducing correction signals into the transmitted signal of each TDS to compensate for the TI at the reception. This, in turn, necessitates reducing the power of the transmitted TDS signal in accordance with the normalized spectrum mask.

A number of works by foreign researchers, for example, [10–15], are devoted to the issues of the efficiency of TDSxDSL in broadband networks, the assessment of the resulting TIs and their compensation. These works present the results of a study of the operation of VDSL2 TDS, G.fast TDS using the “vectoring” system to compensate for TI in broadband networks. The relevance of research in this area of telecommunications is also evidenced by the constantly functioning International Broadband Forum [16].

3. Purpose and objectives of the research

A number of domestic scientific works present the results of studies of the effectiveness of using the TI “vectoring” compensation system when using TDS xDSL on Ukrainian broadband networks [8, 17, 18]. As studies have shown, when compensating the TI between the TDS with the vectoring system, a specific, fundamentally uncompensated TI is generated, since the compensation signal, in turn, is the source of the TI.

The work [18] proposed a method for calculating the signal-to-noise ratio in TDS xDSL, which takes into account the frequency characteristics and additive interference of transmission lines, uncompensated transient interference between mutually influencing TDS. However, the limitation of the useful signal power associated with the normalization of transmitter power caused by the use of the “vectoring” system was not studied in the above and other well-known scientific publications.

The power of the uncompensated TI depends on the parameters of the transient frequency characteristics between the transmission lines of the common transmission medium and the number of operating TDSs.

The technique for estimating the signal-to-noise ratio is of scientific and practical interest. It takes into account the frequency characteristics and additive interference of the transmission line, uncompensated transient interference between mutually influencing TDSs and the limitation of the useful signal power associated with the normalization of the transmitter power, which was not taken into account in known works. It is also interesting to estimate the achievable information transmission speeds of TDS xDSL with the “vectoring” TI compensation system.

4. Estimation of the signal-to-noise ratio in the TDS xDSL with the “vectoring” TI compensation system

The criteria for the effectiveness of using the “vectoring” system will be the increase in the achievable speed of data transmission in the TDSxDSL during parallel operation of the TDS in multi-pair telephone cables when using the “vectoring” system compared to the option of working without it. For this purpose, it is necessary to determine the resulting signal-to-noise ratio at the input of the TDS receiver, taking into account additive noise and TI. Based on this, using the accepted methodology, calculate the TDS data transmission rate achievable under these conditions [19].

Let’s consider a model of a broadband network consisting of L telephone lines of a multi-pair cable (L transmission lines), through which TDS operate using xDSL technology, covered by the vectoring system to compensate for transient interference between these lines (Fig. 1), where l, m=1, 2…L; L –

number of mutually influencing lines; l – number of the affected line; m – number of the influencing line; $H_{l,m}$ – transfer function (TF) between lines l and m; $P_{\text{tr }l}$ – power of the transmitted signal along the l-th line; $P_{\text{rec }l}$ – power of the received signal along the lth line; $\sum P_{XT\ l,m}$ – power of the total transient noise from (L–1) influencing lines into the l-channel.

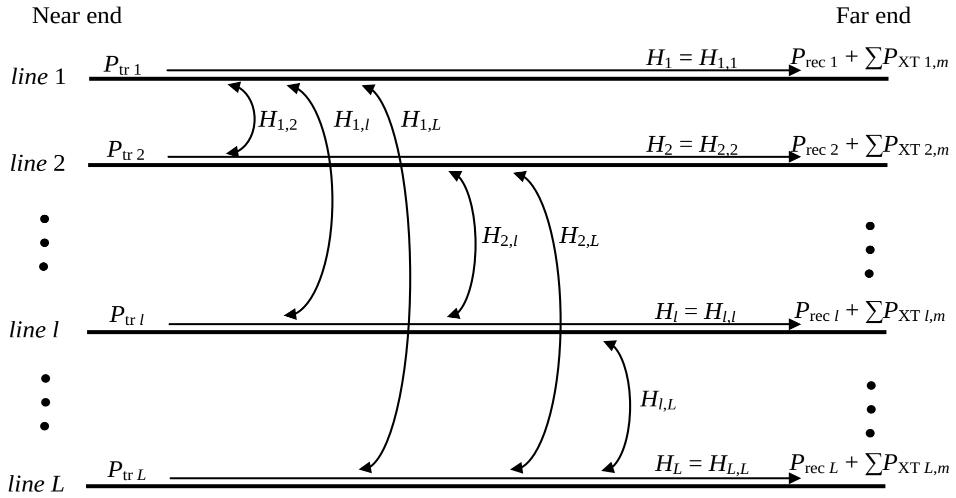

Fig. 1. Diagram L of mutually influencing transmission lines of a multi-pair cable

To implement the vectoring algorithm, it is necessary to know both the intrinsic transfer functions (TFs) of the transmission lines and the TFs between the influencing transmission lines, which are described by the TF matrix $[H_{l,m}]$ from the l-th channel to the m-th channel:

$$[H_{l,m}] = \begin{bmatrix} H_{1,1} & H_{1,2} & .. & H_{1,m} & .. & H_{1,L} \\ H_{2,1} & H_{2,2} & .. & H_{2,m} & .. & H_{2,L} \\ .. & .. & .. & .. & .. & .. \\ H_{l,1} & H_{l,2} & .. & H_{l,m} & .. & H_{l,L} \\ .. & .. & .. & .. & .. & .. \\ H_{L,1} & H_{L,2} & .. & H_{L,m} & .. & H_{L,L} \end{bmatrix}. \quad (1)$$

In matrix (1), the elements of rows and columns are the PFs between the corresponding lines, and the elements of the main diagonal are the own PFs of these lines. PF (1) are frequency dependent functions. In further mathematical operations, the square of the PF – $H^2(f)_{l,m}$ is used, therefore, in order to simplify the analytical expressions, we will use $H_{l,m}$ to denote the function $H^2(f)_{l,m}$. Also, to simplify the recording of our own PFs, instead of two indices with the same value, we will use one index corresponding to the line number – H_l instead of $H_{l,l}$ (this is shown in Fig. 1 by the corresponding entries, for example $H_l = H_{l,l}$).

According to Fig. 1, when a signal with power $P_{\text{tr }l}$ is applied to the input of line l (“Near end line l”), the received signal with power $P_{\text{rec }l}$ will be present at the output of this line (“Far end” line l), and crosstalk from other (L–1) lines with total power $\sum P_{XT\ l,m}$.

In the absence of influences between transmission lines, as well as additive noise channels external to a given system (only thermal noise is taken into account), the signal-to-noise ratio at the receiver input is determined by the expression:

$$SNRa_l = \frac{P_{\text{rec }l}}{P_{\text{noise}}} = \frac{P_{\text{tr }l} \cdot H_l}{N_{\text{add}}}, \quad (2)$$

where $P_{\text{rec }l}$ and P_{noise}, respectively, are the signal and noise power at the input of the TDS receiver;

$P_{\text{tr }l}$ – power of the useful signal during transmission in the l-th channel (at the input of line l);

N_{add} – power of additive white Gaussian noise (AWGN).

If there are mutual influences between transmission lines, it is also necessary to take into account transient interference from all parallel operating $P_{XT\ l}$ information transmission systems. In this case, the signal-to-noise ratio is determined by the expression:

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$$SNR_{XT\ l} = \frac{P_{\text{rec}\ l}}{N_{\text{add}} + P_{XT\ l}} = \frac{P_{\text{tr}\ l} \cdot H_l}{N_{\text{add}} + \sum_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m} \cdot P_{\text{tr}\ m}}, \tag{3}$$

where $P_{\text{tr}\ m}$ is the power of the useful signal during transmission in the m-th channel (at the input of line m).

In accordance with the algorithm of operation of the vectoring system, during transmission in the l-th channel, a signal is added to the transmitted useful signal with power $P_{\text{tr}\ l}$, compensating for transient interference from the m-th channel to the l-th. Power of this signal:

$$Pc_{l,m} = \frac{H_{l,m} \cdot P_{\text{tr}\ m}}{H_l}. \tag{4}$$

The numerator of the fraction in (4) determines the power of the transient noise $P_{XT\ l,m}$ from channel m to channel l, and the denominator allows this transient noise to be recalculated from the output of channel l to its input to generate a compensation signal.

The total power of the crosstalk compensation signal from all (L–1) channels during transmission in the l-th channel is:

$$Pc_l = \sum_{\substack{m=1 \\ m \neq l}}^{L} Pc_{l,m} = \sum_{\substack{m=1 \\ m \neq l}}^{L} \frac{H_{l,m} \cdot P_{\text{tr}\ m}}{H_l}. \tag{5}$$

As a result, a distorted signal with the total power is transmitted to the l-*th* channel:

$$Pv_{\text{tr}\ l} = P_{\text{tr}\ l} + Pc_l. \tag{6}$$

The compensation signal P_{Cl} allows you to compensate for the transient interference $P_{XT\ l}$, but at the same time it is itself a source of transient interference, which determines the fundamental impossibility of completely compensating for transient interference using the vectoring system [17]. The power of uncompensated transient interference is determined by the formula:

$$Pv_{XT\ l} = \sum_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m} \cdot Pc_m = \sum_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m} \cdot \sum_{\substack{n=1 \\ n \neq m}}^{L} \frac{H_{m,n} \cdot P_{\text{tr}\ n}}{H_m}. \tag{7}$$

In this case, expression (3) is transformed as follows:

$$SNRv_l = \frac{P_{\text{rec}\ l}}{N_{\text{add}} + Pv_{XT\ l}} = \frac{P_{\text{rec}\ l} \cdot H_l}{N_{\text{add}} + \sum_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m} \cdot \sum_{\substack{n=1 \\ n \neq m}}^{L} \frac{H_{m,n} \cdot P_{\text{tr}\ n}}{H_m}}. \tag{8}$$

Along with the presence of uncompensated transient interference generated by the compensation signal, it is necessary to take into account one more factor that determines the achievable speeds of mutually influencing G.fast TDS, with the vectoring system. Under the condition of limiting the power of the transmitted signal $P_{\text{vtr}\ l} \leq P_{\text{tr nom}}$, the power of the useful signal $P_{\text{tr}\ l}$ and the power of the compensation signal Pc_l are proportionally reduced.

In this case, the level of the nominal power spectral density (PSD) of the transmitted signal according to the spectrum mask $P_{\text{tr nom}}$ is taken to be less than the level of the maximum PSD of the transmitted p_{mask} by an amount of about 3.5 dB, which are determined by ITU recommendations [2, 3]. Accordingly, the nominal power of the transmitted signal $p_{\text{tr nom}}$ is taken to be approximately 2.2 times less than the maximum power P_{mask}, which makes it possible to take into account the signal crest factor.

Taking into account (5) and (6), the powers of the useful signal and the compensation signal are determined in accordance with the following expressions:

$$P'_{\text{tr}\ l} = P_{\text{tr nom}} \cdot \frac{P_{\text{tr}\ l}}{P_{\text{tr}\ l} + \sum_{\substack{m=1 \\ m \neq l}}^{L} \frac{H_{l,m} \cdot P_{\text{tr}\ m}}{H_l}}, \tag{9}$$

$$P'c_l = P_{\text{tr nom}} \cdot \left(\frac{\sum\limits_{\substack{m=1 \\ m \neq l}}^{L} \frac{H_{l,m} \cdot P_{\text{tr } m}}{H_l}}{P_{\text{tr } l} + \sum\limits_{\substack{m=1 \\ m \neq l}}^{L} \frac{H_{l,m} \cdot P_{\text{tr } m}}{H_l}} \right). \quad (10)$$

Expression (7), taking into account the power limitation of the compensation signal (10), must be rewritten as follows:

$$P'v_{XT\ l} = \sum_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m} \cdot P_{\text{tr nom}} \cdot \left(\frac{\sum\limits_{\substack{n=1 \\ n \neq m}}^{L} \frac{H_{m,n} \cdot P_{\text{tr } n}}{H_m}}{P_{\text{tr } m} + \sum\limits_{\substack{n=1 \\ n \neq m}}^{L} \frac{H_{m,n} \cdot P_{\text{tr } n}}{H_m}} \right). \quad (11)$$

From expression (11) it is clear that the uncompensated transient interference at the input of the *l*-th channel receiver is the sum of transient interference from all other (*L*–1) channels, which is determined by the power of the compensation signals at the output of the *m*-th channel transmitters and the value of the transfer function between the *l*-th and *m*-th channels.

Thus, in the model under consideration, the uncompensated transient interference and the limitation of the power of the TDS signal, along with additive white noise, determine the achievable speed of each TDS.

The signal-to-noise ratio for xDSL TDS with the vectoring system takes the form:

$$SNR'v_l = \frac{P'v_{\text{rec } l}}{P'v_{\text{noise } l}} = \frac{P_{\text{tr nom}} \cdot \left(\frac{P_{\text{tr } l}}{P_{\text{tr } l} + \sum\limits_{\substack{m=1 \\ m \neq l}}^{L} \frac{H_{l,m} \cdot P_{\text{tr } m}}{H_l}} \right) \cdot H_l}{N_{\text{add}} + \left[\sum\limits_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m} \cdot P_{\text{tr nom}} \cdot \left(\frac{\sum\limits_{\substack{n=1 \\ n \neq m}}^{L} \frac{H_{m,n} \cdot P_{\text{tr } n}}{H_m}}{P_{\text{tr } m} + \sum\limits_{\substack{n=1 \\ n \neq m}}^{L} \frac{H_{m,n} \cdot P_{\text{tr } n}}{H_m}} \right) \right]}. \quad (12)$$

In order to be able to obtain qualitative and quantitative estimates of signal-to-noise ratios, we will simplify (12) and further assume that the corresponding parameters of all mutually influencing transmission lines (own PFs and transition PFs) and the characteristics of the TDS (transmitted signal power) operating along them are equal:

$$P_{\text{tr } l} = P_{\text{tr}};\ H_l = H_{\text{OTF}};\ H_{l,m} = H_{\text{TTF}}. \quad (13)$$

Under the accepted assumptions (13), the signal-to-noise ratio for TDS in the absence of transient interference (2), for TDS taking into account transient interference, but without the vectoring system (3) and TDS taking into account transient interference and the vectoring system without restrictions signal power (8) and with signal power limitation (12) can be rewritten as follows:

$$SNRa = \frac{P_{\text{tr}} \cdot H_{\text{OTF}}}{N_{\text{add}}}, \quad (14)$$

$$SNR_{XT} = \frac{P_{\text{tr}} \cdot H_{\text{OTF}}}{N_{\text{add}} + (L-1) \cdot P_{\text{tr}} \cdot H_{\text{TTF}}}, \quad (15)$$

$$SNRv = \frac{P_{\text{tr}} \cdot H_{\text{OTF}}}{N_{\text{add}} + (L-1)^2 \cdot P_{\text{tr}} \cdot \frac{H^2_{\text{TTF}}}{H_{\text{OTF}}}}, \quad (16)$$

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$$SNR'v_l = \frac{P_{\text{tr nom}} \cdot H_{\text{OTF}} \cdot K_{P\,\text{norm}}}{N_{\text{add}} + \left[P_{\text{tr nom}} \cdot (L-1)^2 \cdot \frac{H^2_{\text{TTF}}}{H_{\text{OTF}}} \cdot K_{P\,\text{norm}} \right]}. \tag{17}$$

In order to simplify formula (12), the coefficient $K_{P\,norm}$ is introduced into formula (17), which we will call the useful signal power normalization coefficient:

$$K_{P\,\text{norm}} = \frac{1}{1 + (L-1) \cdot \frac{H_{\text{TTF}}}{H_{\text{OTF}}}}, \tag{18}$$

$$1 \geq K_{P\,\text{norm}} > 0.$$

5. Evaluation of the effectiveness of G.fast TDS when compensating for transient interference with the vectoring system

Using the signal-to-noise ratios (14 – 18), we calculate the achievable information transmission rates in a broadband access network using multi-pair telephone cables TPP-0.4, taking into account the compensation of transient interference by the vectoring system without limitation (16) and with limited signal power (17). The choice of TPP type cable for the calculation is due to the fact that it is the most common on the existing fixed broadband access network in Ukraine, and its electrical characteristics are inferior to those of the twisted pair cable. In this way, in a certain sense, a lower estimate of the achievable information transmission rates will be obtained when transient interference is compensated by the vectoring system.

The achievable speed of the G.fast TDS in a system of mutually influencing TDS was calculated using the method presented in [19] with the following initial data:

– G.fast TDS parameters comply with Rec. G.9700 and G.9701 MCE-T [2, 3];
– frequency characteristics of the TPP-0.4 cable were determined from [1, 8, 18];
– line length – 25…250 m;
– number of parallel operating G.fast TDS – 1…100;
– additive interference was taken into account as AWGN with a PSD level of –140;120 dBm/Hz.

Fig. 2 and 3 present the results of calculating, respectively, the absolute (in Mbit/s) and relative (in %) reduction in the information transmission rate of the G.fast TDS with the vectoring system when limiting the signal power relative to the option without power limitation and AWGN=140 dBm/Hz.

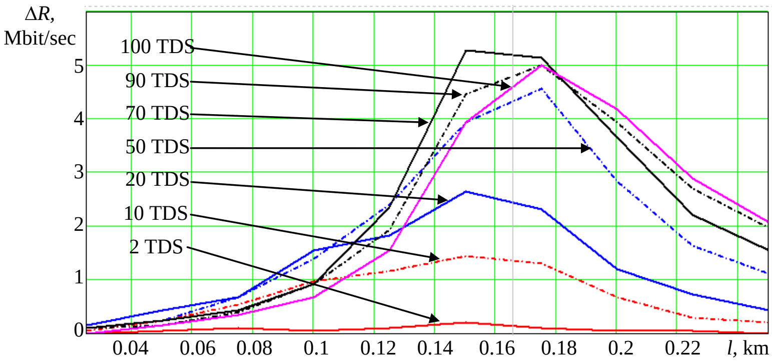

Fig. 2. Reducing the transmission data speed of TDS G.fast by limiting the signal power when using the vectoring system (TPP-0.4; AWGN=–140 dBm/Hz)

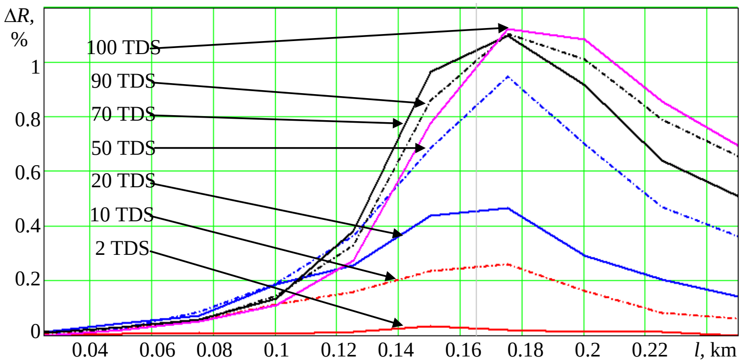

Fig. 3. Relative reduction in the transmission data speed of TDS G.fast due to limiting the signal power when using the vectoring system (TPP-0.4; AWGN=–140 dBm/Hz)

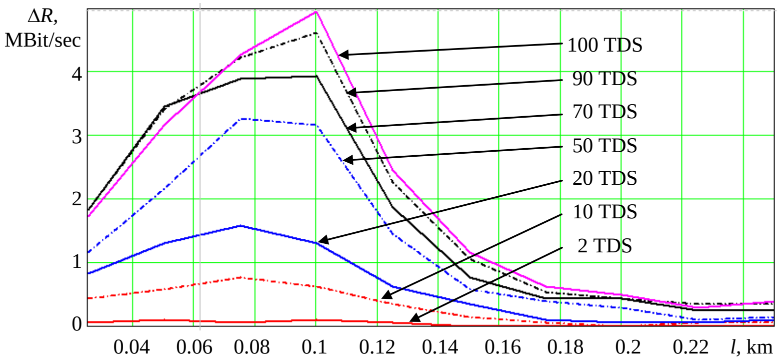

Fig. 4. Reducing the transmission data speed of TDS G.fast by limiting the signal power when using the vectoring system (TPP-0.4; AWGN=–120 dBm/Hz)

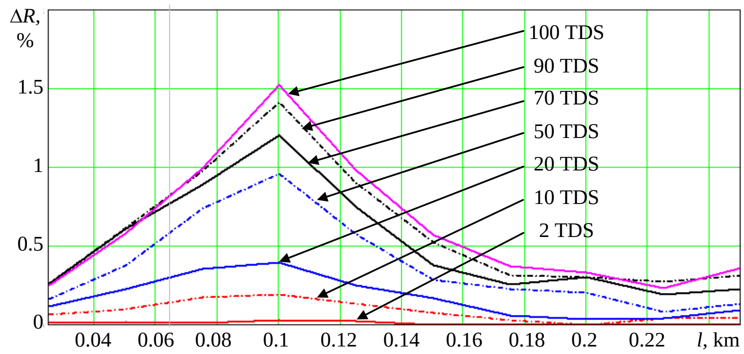

Fig. 5. Relative reduction in the data transmission speed of TDS G.fast due to limiting the signal power when using the vectoring system (TPP-0.4; AWGN=–120 dBm/Hz)

Based on the analysis of the results of calculating the information transmission speed presented in Fig. 2 – 5 the following conclusions can be drawn:

– transient interference significantly limits the speed of information transmission during parallel operation of xDSL TDS over multi-pair telephone cables;

– the use of the “vectoring” system is an effective method of increasing the achievable speed of information transmission of xDSL TDS;

– limiting the signal power when using the vectoring system leads to a slight decrease in the transmission speed. So, when working in parallel up to 100 TDS G.fast at an additive interference level of –140 dBm/Hz) the transmission speed is reduced by no more than 5.5 Mbit/s or 1.15% of the total speed when operating without power limitation;

– limiting the signal power when using the vectoring system when operating G.fast TDS in conditions of increased additive interference (with a level of –120 dBm/Hz) with parallel operation of up to 100 TDS leads to a decrease in the information transfer rate by no more than 5 Mbit/ s or 1.5% of the total speed without power limitation.

The main factor limiting the achievable information transmission rate of xDSL TDS when using the vectoring system is uncompensated crosstalk.

The insignificant effect of limiting the signal power on the achievable information transmission rate of the G.fast TDS when using the vectoring system is explained by the fact that, according to expression (17), when limiting the power of the transmitted signal, not only the power of the received useful signal decreases (the numerator of expression (17)), but and the power of uncompensated interference (denominator of expression (17)). But the power of the transmitted TDS signal depends both on the transmitted compensation signal, which is objectively insignificant, and on the value of the useful signal power normalization coefficient $K_{P\,\mathrm{norms}}$(18).

Let us evaluate the role of the latter in limiting signal power when using the vectoring system. Figure 6 shows the frequency dependences of the power normalization coefficient of the useful signal KP norms during parallel operation of 100 G.fast TDS with a line length from 50 to 250 meters. And in Fig. 7 shows graphs of the distribution of the number of bits of transmitted information b by carrier frequencies, the sum of which determines the information transmission rate of the G.fast TDS.

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From Fig. 6 it follows that the power of the transmitted signal at carrier frequencies above 100 MHz under certain conditions can be reduced to 58% of the rated power. But if we compare the values of KP norms with the corresponding results of transmitted bits of information in Fig. 7, it can be seen that carrier frequencies with low $K_{P\ \text{norms}}$ are not used to transmit information, primarily due to the high line attenuation. As a result, we can assume that the normalization coefficient for the power of the useful signal actually decreases slightly – $K_{P\ \text{norms}} \geq 0.79$, otherwise carrier frequencies are not used to transmit information, as a result of which the power of the transmitted signal decreases.

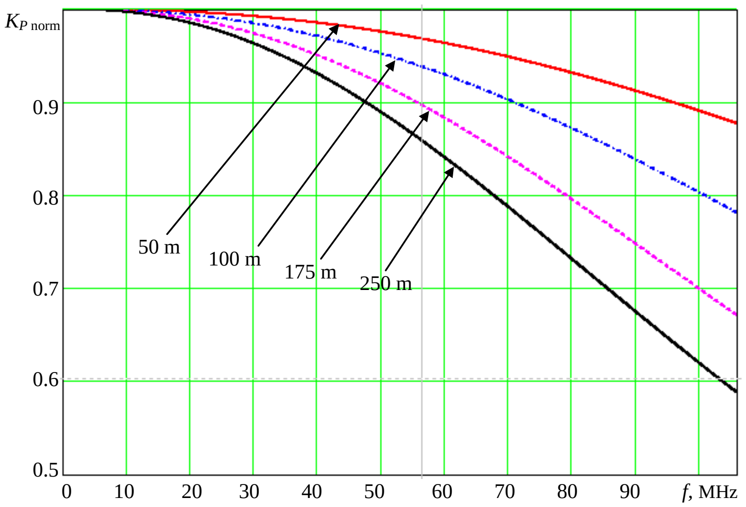

Fig. 6. Frequency dependence of the useful signal power normalization coefficient when using the vectoring system (TPP-0.4; 100 TDS)

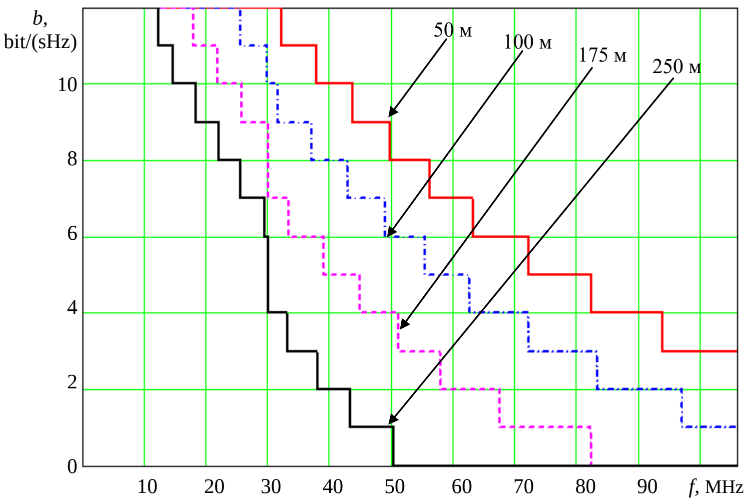

Fig. 7. Distribution of bits across the G.fast TDS carrier frequencies when using the vectoring system with power limitation (TPP-0.4; 100 TDS; AWGN=–140 dBm/Hz)

6. Conclusions

The article provides an assessment of the effectiveness of transmission data systems over xDSL digital subscriber lines using the "vectoring" transient interference compensation system between TDSs.

A method for calculating the signal-to-noise ratio in the TDS xDSL is proposed, which takes into account the frequency characteristics and additive noise of lines, uncompensated transient interference between mutually influencing TDSs and the limitation of the useful signal power associated with the normalization of transmitter power caused by the use of the vectoring system.

The results of modeling the parallel operation of up to 100 TDSs of G.fast technology over multi-pair cables of TPP-0.4 type with a line length from 25 to 250 meters are presented.

The influence on the achievable transmission speed of TDS of the limitation of the power of the useful signal when using the vectoring system is assessed. It has been determined that the main reason for limiting the achievable transmission speed of TDS when using the vectoring system is the uncompensated TI. Limiting the power of the useful signal leads to a decrease in the data transmission speed by no more than 1.5%.

The proposed methodology for assessing the signal-to-noise ratio and the achievable data transmission speed of TDS using xDSL technologies with vectoring compensation systems can be useful in the design and construction of fixed broadband access networks using multi-pair telephone cables and twisted pair cables as a transmission medium.

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