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# Speed Estimation of Broadband Access to Internet via xDSL Technology

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**Abstract**—The paper proposes a method for estimating the speed of broadband Internet access using information transmission systems (ITS) via xDSL technology and utilizing the vectoring system of crosstalk compensation between ITS when operating via access networks. The estimation accounts for additive interference, uncompensated crosstalk between interdependent ITS caused by using the vectoring system. The attainable access speed using the G.fast protocol was estimated depending on specifications of transmission lines, the number of ITS in operation, and the use of vectoring system.

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## 1. INTRODUCTION

To build networks with fixed broadband access (BA) to Internet, both optical cables and information transmission systems (ITS), on the one hand, and multi-pair telephone cables, “twisted pair”-type cables, and ITS using xDSL technology (xDSL ITS), on the other hand, are widely used [1]. The most efficient G.fast ITS are capable to provide information transfer rates over BA networks up to 1 Gbit/s and higher [2], [3].

The xDSL ITS technologies are constantly being improved and developed. The latest upgrade of Recommendation G.9701 (G.fast ITS) dates back to March 2019. MGfast ITS that provide multi-gigabit transmission rates over multi-pair cables have been developed and standardized [4], [5]. The development of xDSL technologies is on the way to increase the data transfer over BA networks to terabit rates [6], [7].

For xDSL ITS using transmission lines of fixed BA network, the limitation of information transfer rate is caused along with additive white noise and the inherent attenuation of the lines, also by crosstalk between ITS working in a common transmission medium employing multi-pair cables.

Currently, the high transmission data rate of xDSL ITS operating in a common transmission medium is ensured through the use of a system of crosstalk compensation (suppression) that is called vectoring [8], [9]. The vectoring algorithm includes the measurement of crosstalk from ITS operating in a common transmission medium, and the introduction of correction signals into transmitted signal of each ITS to compensate them at the receiving side. This, in turn, necessitates a reduction of the power of transmitted useful ITS signal in accordance with the normalized spectrum mask.

A number of papers by foreign researchers are devoted to the efficiency considerations of xDSL ITS in BA networks, and to the estimation of the resulting crosstalk and its compensation [10]–[15]. Another proof of the relevancy of studies in this telecommunications field is the continuously functioning International Broadband Forum [16]. These papers present the results of studying the operation of VDSL2 ITS and G.fast ITS using the vectoring system in BA networks with characteristics of transmission lines that differ from those used in Ukraine. Thus, the acquired estimations do not reflect the application efficiency of xDSL ITS in BA networks of Ukraine.

A number of domestic scientific papers present the results of studies on the efficiency in application of vectoring crosstalk suppression system when using xDSL ITS in BA networks of Ukraine [8], [17]. According to the studies, the compensation of crosstalk between ITS and the vectoring system, another

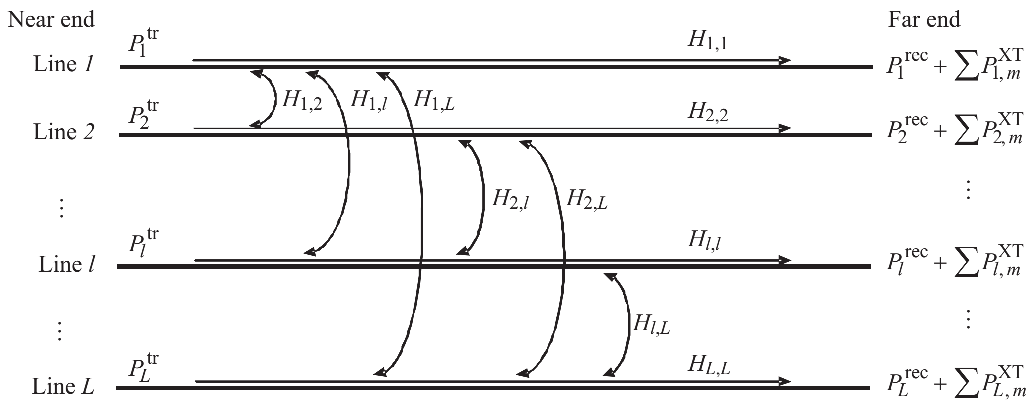



**Fig. 1.** Diagram of $L$ interdependent transmission lines of BA network.

specific crosstalk is produced that fundamentally cannot be compensated since the compensation signal, in turn, is a source of crosstalk.

The power of uncompensated crosstalk depends on parameters of transient frequency responses between the lines in the common transmission medium and the number of operating ITS. It is of scientific and practical interest to develop a methodology for estimating the achievable speeds of the Internet BA using the xDSL technology with the vectoring crosstalk compensation system.

## 2. SNR ESTIMATING IN xDSL ITS WITH VECTORING CROSSTALK COMPENSATION SYSTEM

In order to estimate the attainable data transmission rate of xDSL ITS with the vectoring crosstalk compensation system in the network of fixed BA to Internet, it is necessary, in turn, to assess the efficiency of applying the vectoring system, i.e., to determine the resulting signal-to-noise ratio (SNR) at the input of ITS receiver. Then, it is necessary to calculate the attainable transmission rate under these conditions using an established methodology [18].

Let us consider a model of fixed BA network that includes a system of $L$ transmission lines used by xDSL ITS, which are covered by the vectoring system for the purpose of crosstalk compensation between the specified lines (Fig. 1), where $l, m = 1, 2, \ldots, L$; $L$ is the number of interdependent lines; $l$ is the number of the line subjected to influence; $m$ is the number of the influencing line; $H_{l,m}$ is the transfer function (TF) between lines $l$ and $m$; $P_l^{tr}$ is the power of the signal transmitted over the $l$-th line; $P_l^{rec}$ is the power of the signal received over the $l$-th line; and $\Sigma P_{l,m}^{XT}$ is the total crosstalk power from ($L$–1) lines influencing the $m$-th channel.

In the general case, transformations of signals transmitted over transmission lines and the crosstalk between influencing transmission lines of the BA network model (Fig. 1) are described by TF matrix $[H_{l,m}]$ $l, m = 1, \ldots, L$:

$$[H_{l,m}] = \begin{bmatrix} H_{1,1} & H_{1,2} & \cdots & H_{1,m} & \cdots & H_{1,L} \\ H_{2,1} & H_{2,2} & \cdots & H_{2,m} & \cdots & H_{2,L} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ H_{l,1} & H_{l,2} & \cdots & H_{l,m} & \cdots & H_{l,L} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ H_{L,1} & H_{L,2} & \cdots & H_{L,m} & \cdots & H_{L,L} \end{bmatrix}, \tag{1}$$

where the elements of rows and columns are TF between corresponding transmission lines, while the elements of the main diagonal are the proper TF of these lines. All TF are frequency-dependent functions, therefore, in what follows we use designations $H(f)_{l,m}$ or $H_{l,m}$.

In accordance with Fig. 1, upon applying a signal with power $P_l^{\text{tr}}$ to the input of the $l$-th line (“Near end”), at the output of this line (“Far end”) there will be a received signal with power $P_l^{\text{rec}}$ and the crosstalk from other $(L-1)$ lines with total power $\Sigma P_{l,m}^{\text{XT}}$.

If there is no crosstalk between the transmission lines and there are no external for this system lines of additive interference (only thermal noise is taken into account), SNR at the receiver input is determined by the following expression:

$$\text{SNR}_l = \frac{P_l^{\text{rec}}}{P_{\text{n}}} = \frac{P_l^{\text{tr}} H_{l,l}^2}{N_{\text{AWGN}}}, \tag{2}$$

where $P_{\text{n}}$ is the power of noise at the ITS receiver input; $N_{\text{AWGN}}$ is the power of additive white Gaussian noise (AWGN).

In case of mutual influence between transmission lines, it is necessary to take into account crosstalk $P_l^{\text{XT}}$ from all working ITS. In this case, SNR is defined as:

$$\text{SNR}_l^{\text{XT}} = \frac{P_l^{\text{rec}}}{N_{\text{AWGN}} + P_l^{\text{XT}}} = \frac{P_l^{\text{tr}} H_{l,l}^2}{N_{\text{AWGN}} + \sum\limits_{\substack{m=1 \\ m \neq l}}^{L} H_{l,m}^2 P_m^{\text{tr}}}, \tag{3}$$

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

In accordance with the algorithm of vectoring system operation, when transmission takes place in the $l$-th channel, a signal compensating the crosstalk from the $m$-th channel into the $l$-th channel is added to the transmitted useful signal having power $P_l^{\text{tr}}$. The power of this signal is as follows:

$$P_{l,m}^{\text{c}} = \frac{H_{l,m}^2 P_m^{\text{tr}}}{H_{l,l}^2}. \tag{4}$$

The numerator in expression (4) determines the crosstalk power $P_{l,m}^{\text{XT}}$ from the $m$-th into $l$-th channel, and the denominator allows us to recalculate this crosstalk from the output of the $l$-the channel, to its input for forming the compensation signal.

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

$$P_l^{\text{c}} = \sum_{\substack{m=1 \\ m \neq l}}^{L} P_{l,m}^{\text{c}} = \sum_{\substack{m=1 \\ m \neq l}}^{L} \frac{H_{l,m}^2 P_m^{\text{tr}}}{H_{l,l}^2}. \tag{5}$$

Hence, a pre-distorted (“pd”) signal is transmitted in the $l$-th channel with the total power:

$$(P_l^{\text{tr}})^{\text{pd}} = P_l^{\text{tr}} + P_l^{\text{c}}. \tag{6}$$

Compensation signal $P_l^{\text{c}}$ allows us to compensate $P_l^{\text{XT}}$ crosstalk, but at the same time it becomes a source of crosstalk on its own [17] that determines the fundamental impossibility of crosstalk total compensation by using a vectoring system.

The power of uncompensated crosstalk is determined by the following formula:

$$(P_l^{\mathrm{XT}})^{\mathrm{pd}} = \sum_{\substack{m=1\\ m\neq l}}^{L} H_{l,m}^2 P_m^{\mathrm{c}} = \sum_{\substack{m=1\\ m\neq l}}^{L} H_{l,m}^2 \sum_{\substack{n=1\\ n\neq m}}^{L} \frac{H_{m,n}^2 P_n^{\mathrm{tr}}}{H_{m,m}^2}. \tag{7}$$

In this case, expression (3) is transformed to the form:

$$\mathrm{SNR}_l^{\mathrm{pd}} = \frac{P_l^{\mathrm{rec}}}{N_{\mathrm{AWGN}} + (P_l^{\mathrm{XT}})^{\mathrm{pd}}} = \frac{P_l^{\mathrm{tr}} H_{l,l}^2}{N_{\mathrm{AWGN}} + \sum\limits_{\substack{m=1\\ m\neq l}}^{L} H_{l,m}^2 \sum\limits_{\substack{n=1\\ n\neq m}}^{L} \frac{H_{m,n}^2 P_n^{\mathrm{tr}}}{H_{m,m}^2}}. \tag{8}$$

Along with the presence of uncompensated crosstalk produced by the compensation signal, it is necessary to take into account another factor that determines attainable speeds of interdependent G.fast ITS using vectoring system, i.e., the power limitation $(P_l^{\mathrm{tr}})^{\mathrm{pd}}$ of transmitted useful ITS signal in accordance with the normalized mask of power spectral density (PSD) of transmitted signal $P_{\mathrm{nom}}^{\mathrm{tr}}$ of spectrum: $(P_l^{\mathrm{tr}})^{\mathrm{pd}} \le P_{\mathrm{nom}}^{\mathrm{tr}}$.

In order to simplify further analysis, let us assume that the corresponding parameters of all interdependent transmission lines (proper TF (PTF) and crosstalk TF (CTF)) and ITS parameters (power of transmitted signal) using them are equal:

$$P_l^{\mathrm{tr}} = P^{\mathrm{tr}}, \quad H_{l,l}^2 = H_{\mathrm{PTF}}^2, \quad H_{l,m}^2 = H_{\mathrm{CTF}}^2. \tag{9}$$

Under the adopted assumptions (9), SNR (3) for ITS with crosstalk taken into account, but without vectoring system, and ratio (8) for ITS with due regard for crosstalk and the vectoring system can be rewritten in the following way:

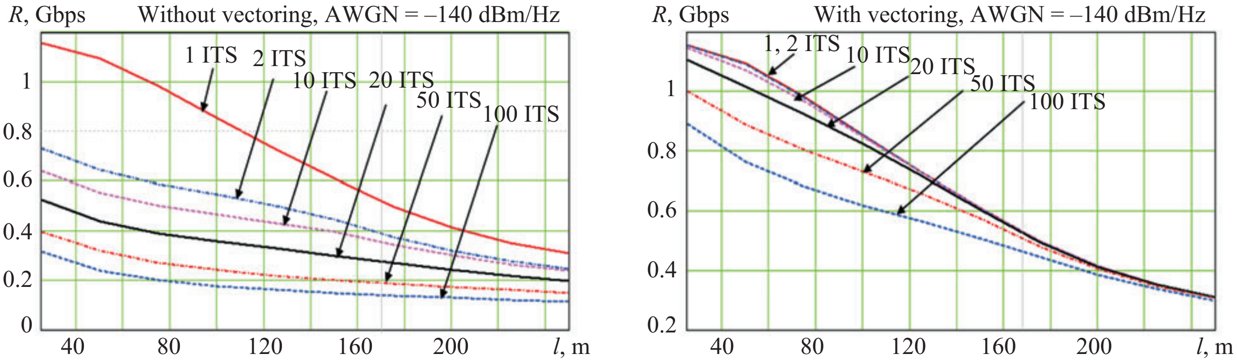
$$\mathrm{SNR}^{\mathrm{XT}} = \frac{P^{\mathrm{tr}} H_{\mathrm{PTF}}^2}{N_{\mathrm{AWGN}} + (L-1) P^{\mathrm{tr}} H_{\mathrm{CTF}}^2}, \tag{10}$$

$$\mathrm{SNR}^{\mathrm{pd}} = \frac{P^{\mathrm{tr}} H_{\mathrm{PTF}}^2}{N_{\mathrm{AWGN}} + (L-1)^2 P^{\mathrm{tr}} \frac{(H_{\mathrm{CTF}}^2)^2}{H_{\mathrm{PTF}}^2}}. \tag{11}$$

Formulas (10) and (11) make it possible to estimate SNR for xDSL ITS with and without the vectoring algorithm.

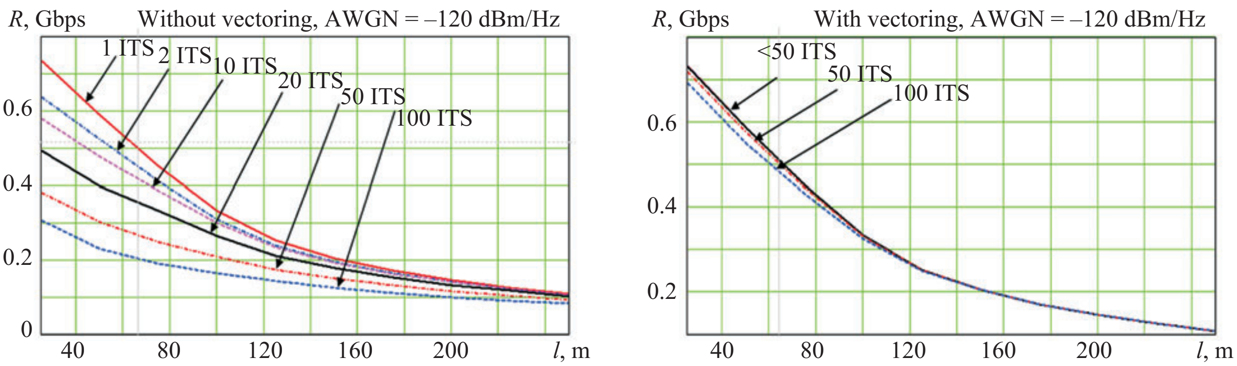
## 3. ESTIMATING INFORMATION TRANSMISSION RATE OF G.FAST ITS USING NETWORK OF FIXED BA TO INTERNET

Using SNR estimates (10) and (11), we can calculate the attainable information transfer rates of G.fast ITS in a BA network using multi-paired telephone cables TP-0.4 [1], [8]. The choice of TP type cables for the calculation is related to the fact that it is most commonly used in domestic BA network, while its electric specifications are much inferior to the specifications of the twisted pair type cable. Thus, the lower estimate of attainable information transmission speed will be obtained. We will calculate the transmission rates using the method described in [18] with due regard for the crosstalk, but without using the vectoring system (10) and with due regard for the crosstalk compensation by the vectoring system (11).




(a) (b)

**Fig. 2.** Information transmission rate of G.fast ITS with due regard for crosstalk with (b) and without (a) vectoring (TP-0.4; AWGN = –140 dBm/Hz).




(a) (b)

**Fig. 3.** Information transmission rate of G.fast ITS with due regard for crosstalk with (b) and without (a) vectoring (TP-0.4; AWGN = –120 dBm/Hz).

The attainable information transfer rate was calculated using the following initial data of G.fast ITS:

– parameters of G.fast ITS comply with Recommendations G.9701 and G.9700 ITU-T [2], [3];

– frequency plan up to 106 MHz;

– main frequency (carrier spacing) is 51.75 kHz;

– working channels (carrier frequencies) are 39–2047;

– cable frequency characteristics were determined according to papers [1], [8], [17];

– line length is 25–250 m;

– the number of G.fast ITS working in parallel is 1–100;

– additive interference was accounted for as AWGN with PSD (power spectral density) equal to –140 and –120 dBm/Hz.

The results of calculating the relationship of the information transmission rate of G.fast ITS as a function of the transmission line length in the absence of external interference (AWGN = –140 dBm/Hz) with due regard for crosstalk with and without using the vectoring system are presented in Fig. 2. Each curve in Fig. 2 corresponds to a specific number of ITS that work in multi-pair telephone cable and exercise mutual influence on one another.

Similar results of calculating the information transfer rates of G.fast ITS for the AWGN variant with PSD level of –120 dBm/Hz are presented in Fig. 3.

## 4. DISCUSSION OF RESULTS

The presented estimates of data transmission rate of G.fast ITS via the fixed BA network confirm (within the framework of above assumptions) the physical objectivity and efficiency of the technique proposed for calculating the speed of xDSL ITS while using the vectoring crosstalk compensation system.

The analysis of calculation results of information transmission rate of G.fast ITS that are presented in Figs. 2 and 3 allows us to draw the following conclusions.

1. The crosstalk tangibly limits the information transmission rate of G.fast ITS while using networks of fixed BA to Internet. Hence, in the case of 10 ITS in operation, the speed can decrease by 1.25–2 times, while in the case of 100 ITS in operation, the corresponding speed can decrease by 2–5 times.

2. The application of vectoring system makes it possible to significantly enhance the attainable data transmission rate of G.fast ITS as compared with operation without crosstalk compensation. In this case, the transmission rate reduction as compared with an ideal variant (in the absence of crosstalk) during 10 ITS being in operation does not exceed 2%, while in case of 100 ITS in operation this reduction is no more than 30%.

3. In the case of using a vectoring system, additive interference is the main cause of reducing the data transmission rate. If the level of AWGN noise is raised to –120 dBm/Hz, the transmission rate reduction of G.fast ITS as compared with variant AWGN = –140 dBm/Hz amounts to 1.25–3 times depending on the line length and the number of operating transmission systems.

4. The power limitation of transmitted signal while using a vectoring system leads to an insignificant reduction of data transmission rate. Hence, in the case of up to 100 ITS being in operation, the speed can be reduced by no more than 5.5 Mbit/s or 1.15% of the total transmission rate without power limitation.

## 5. CONCLUSIONS

The paper proposes a technique for estimating the speed of broadband access to Internet using information transmission systems xDSL ITS and utilizing the vectoring system of crosstalk compensation. This technique takes into account, along with additive interference and signal attenuation in transmission line, the uncompensated crosstalk between interdependent ITS operating within the common transmission medium. The results of simulating the BA network containing up to 100 G.fast ITS and using the vectoring system of crosstalk compensation and the estimates of attainable access speed to Internet have been presented.

The proposed technique for estimating the attainable information transmission rate using the xDSL technologies can be applied in solving the tasks of designing and constructing networks of fixed broadband access to Internet employing multi-pair telephone cables and twisted pair type cables.

## CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

## ADDITIONAL INFORMATION

The initial version of this paper in Ukrainian is published in the journal “Izvestiya Vysshikh Uchebnykh Zavedenii. Radioelektronika,” ISSN 2307-6011 (Online), ISSN 0021-3470 (Print) on the link http://radio.kpi.ua/article/view/S0021347022080052 with DOI: 10.20535/S0021347022080052.

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