Estimating losses from transient and intersymbol distortions in hybrid fiber-coaxial television network

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Abstract – **Modern hybrid cable television networks use high-speed optical trunk lines as backbone network. When estimating the optimum number of amplifying sections within the optical trunk line, the power potential of the system is used. This potential is the difference between the maximum signal level and the signal losses inside the transmission line and termination devices. These are the losses caused by the signal fading, the losses resulting from transient and intersymbol distortions plus the losses caused by additive noise. The primary goal is to offer a practical approach for estimating the signal losses, resulting from transient and inter-symbol distortions, depending on the physical parameters of the transmission line and the optical equipment in use.**

Keywords – **HFC CATV, WDM, optical amplifier, photodiode receiver, signal level, nonlinear distortion**

I. Introduction

As a transmission medium, fiber optic cables are widely used in backbone networks for signal transmission in hybrid fiber-coaxial television networks. Wavelength division multiplexing systems are also widely used when building optical trunk–lines [1,2,3]. Structural diagram of an optical system for transmission with wavelength multiplexing is shown in fig. 1.

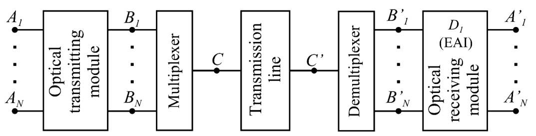

Fig. 1. Structural diagram of an optical system for data transmission with wavelength-division multiplexing

The transmission line can be presented as amplifying sections connected in series each of which has a structure that is shown in fig. 2 [2,3,8]. p_S is the signal level in the transmission line, $p_S – A_{NL}$ and $p_S – A_{ISD}$ are respectively the differences between the system signal level and the group signal protectability level from the total power of nonlinear transient distortions and the losses due to intersymbol distortions.

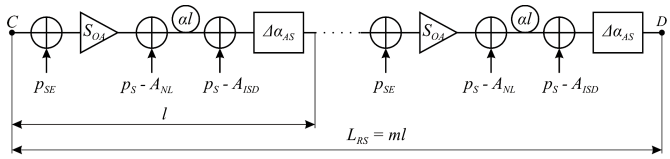

Fig. 2. Structural diagram of amplifying sections

The need of periodic amplification of signal is causally related to amplitude losses and the dispersion expansion of code pulses. Nonlinear distortions in optical fibers are caused by phenomena arising from inadmissible high levels of transmitted signals [5,9]. Effects related with light scattering are characterized by threshold level which is highly sensitive to the length of the amplifying section. Nonlinear effects related with self-phase modulation and four wave mixing characterize systems with wavelength division multiplexing and exert a great overall influence [5,6].

Optimum number of amplifying sections in optical trunk-lines of HFC networks can be implemented by applying an iterative approach. Through series of iterations a solution is found which for a set number of amplifying sections m_j for the current iteration will yield percentage error that satisfies the inequality

$$\delta_{Cj} = \left|\Delta A_E(m_j) / A_{N_E}(m_j)\right| \le 0{,}1 , \qquad (1)$$

where $\Delta A_E(m_j)$ is the difference between the maximum possible and total of real signal losses given at the elecrtonical amplifier input (EAI) (fig. 1); $A_{N_E}(m_j)$ – is the minimum admissible signal level at the amplifier input.

Maximum admissible total losses of signal in optical network can be expressed as

$$\Delta A_{\max} = A_{\max} - A_N , \qquad (2)$$

where $A_{\max}$ – is the maximum possible protectability of signal from thermal noise at the amplifier input (EAI) with no optical amplifier and ideal devices, A_N – is the norm of signal protectability level which can be estimated if the error ratio of the regenerator is determined.

Total real losses of signal within the optical system can be expressed as

$$\Delta A_\Sigma = \Delta A_S + \Delta A_{TD} + \Delta A_{ISD} + \Delta A_{AN} , \qquad (3)$$

where ΔA_S – are the signal losses due to signal fading in the transmission line; ΔA_{TD} – losses due to all kinds of transient distortions (linear in the termination devices and nonlinear in the optical amplifiers); ΔA_{ISD} – is for the losses due to intersymbol distortions (in the termination devices and the transmission line); ΔA_{AD} – are losses due to all kinds of additive noise (in the termination devices and transmission line), with the exception of the thermal noise of the electronic amplifier which is taken into consideration when estimating $A_{\max}$. Therefore, in order to achieve a realizable optical

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transmission system with wavelength division multiplexing there should be fulfilled the condition of

$$\Delta A_{\max} \geq \Delta A_{\Sigma}\,, \qquad (4)$$

By substituting Eqs.(2) and (3) in Eq.(4) we get

$$A_{\max} - \Delta A_S - \Delta A_{TD} - \Delta A_{ISD} - \Delta A_{AN} \geq A_N\,. \qquad (5)$$

Then the difference between maximum possible and the total real signal losses considering the number of amplifying sections m will be

$$\Delta A(m) = \Delta A_{\max}(m) - \Delta A_{\Sigma}(m)\,. \qquad (6)$$

Conversion of Eq. (6) by using Eq. (5) for the input of electronic amplifier will appear as

$$\begin{aligned}\Delta A_E(m) &= A_{\max_E}(0) - \Delta A_{S_E}(m) - \Delta A_{TD_E}(m)\\ &- \Delta A_{ISD_E}(m) - \Delta A_{AN_E}(m) - A_{N_E}(m) \geq 0,\end{aligned} \qquad (7)$$

where the maximum signal level in the transmission line, taking into consideration the losses in the termination devices (the receiving and transmitting optical modules, multiplexers and demultiplexers) is estimated as

$$A_{\max_E}(0) = A_{\max_E} - \Delta A_{S_E}(0) - \Delta A_{TD_E}(0) - \Delta A_{ISD_E}(0)\,. \qquad (8)$$

In Eq. (8) $A_{\max_E}$ is the maximum level of signal ($S_{APD} = 0$).

For the purpose of analysis in Eqs. (7) and (8) of the influence of individual types of losses, they are conditionally divided into two separate groups: those depending on the number of amplifying sections m in the transmission line and those which do not depend on the number of amplifying sections (i.e. the losses at the termination devices when m=0).

Complete analysis of Eqs. (7) and (8) to determine all components which are set in the expressions. The aim of this paper is to determine the last two components of Eq. (7) – the losses caused by transient $\Delta A_{TD}(m)$ and intersymbol distortions $\Delta A_{ISD}(m)$ in the transmission line.

It is advisable to make estimations for the signal losses for the electronic amplifier input (fig. 1), i.e. index "E" refers to EAI.

II. Estimation of Losses Caused by Transient and Intersymbol Distortions in the Transmission Line

A. Estimation of signal protectability level from the transient distortions in function of the number of channels in a single optical amplifier

If the average power of the signal in N channels at the optical amplifier output is constant, then the value in the k channel of signal protectability level from transient distortions which are composite third order (CTB) distortions arising in the optical amplifier [1] will be

$$\begin{aligned}A_{TD}(f_k) &= 10\lg\left(NC_1P_Sg_1(f_k)\right)/\left(N^3C_3P_S^3g_3(f_k)\right) =\\ &= A_{NL} + 10\lg\left(g_1(f_k)/g_3(f_k)\right),\end{aligned} \qquad (9)$$

where $A_{NL} = 10\lg((NC_1P_S)/(N^3C_3P_S^3))$ is the group signal protectability level from the total power of nonlinear transient distortions; NC_1P_S and $N^3C_3P_S^3$ are the real values of signal power at the output of the optical amplifier; C_1 and C_3 are decomposition coefficients of the expression for the output power of the optical amplifier in series concerning the exponents of the input power; $g_1(f_k)$ and $g_3(f_k)$ are the normalized spectrums from first and third order for channel k with central frequency f_k. These transient distortions in optical amplifiers are referred to as four-wave mixing (FWM) [2,5]. For normalized spectrums of composite third order distortions in optical amplifier it is possible to write

$$g_3(f) = g_2(f) * g_1(f)\,, \qquad (10)$$

where * means a convolution of normalized spectrums, $g_2(f)$ – normalized spectrum of nonlinear second order distortions (CSO), $g_1(f)$ – normalized spectrum of the output signal. It can be expressed as the sum of positive and negative spectrums which are necessary for considering the convolution of all contributing frequencies that occur as lower and upper sidebands of the spurious amplitude modulation caused by the nonlinearity of the optical amplifier

$$g_1(f) = \sum_{1}^{N} g(f_k) + \sum_{N}^{1} g(-f_k) = 0{,}5/N\,. \qquad (11)$$

The normalized second order spectrum is composed of following three components

$$g_2(f_x) = g_{21}(f_{x1}) + g_{22}(f_{x2}) + g_{23}(f_{x3})\,. \qquad (12)$$

All components in Eq. (12) can be expressed by the variable x which is changed by 1 from $-(N-1)$ to $(N-1)$. This also is valid for the frequencies f_{x1}, f_{x2}, f_{x3} within the discrete frequency interval $\Delta=|f_k - f_{k-1}|$ for each k.

The first component of the second order normalized spectrum will be

$$g_{21}(f_{x1}) = \left(n - |x|\right)/\left(4N^2\right), \qquad (13)$$

where the frequency corresponding to x is determined as $f_{x1} = -(f_1 + f_N) - x\Delta$ in the frequency range from $-2f_N$ to $-2f_1$.

The second component then will be

$$g_{22}(f_{x2}) = \left(n - |x|\right)/\left(2N^2\right), \qquad (14)$$

and the frequency corresponding to x is determined as $f_{x2} = x\Delta$ in the frequency range from $-(f_N - f_1)$ to $(f_N - f_1)$.

The third component will be

$$g_{23}(f_{x3}) = \left(n - |x|\right)/\left(4N^2\right), \qquad (15)$$

and frequency corresponding to x: $f_{x3} = (f_1 + f_N) + x\Delta$ in the frequency range from $2f_1$ to $2f_N$.

The output spectrum of third order transient distortions is convolution of the obtained normalized second order spectrums with the output spectrum [2,7,8].

The normalized third order spectrum with number k obtained by the convolution of $g_{22}(f_{x2})$ with $f_{x2} > 0$ and $g_1(f)$ with $f > 0$, can be expressed as

$$g'_{32}(k) = g'_{32}(f_{32}) = \left(S_{N-k}^{N-2}\right)/\left(2N^2\right), \qquad (16)$$

where each number of the channel k has a corresponding channel frequency f_k; S_{N-k}^{N-2} is the sum of the members of the arithmetic progression from $(N - k)$ to $(N - 2)$.

It is evident that the operating range of frequencies must be selected k from 2 to N in accordance with the minimum third order frequency spectrum.

The sum of the terms of the arithmetic progression from a to b will be

$$S_a^b = 0{,}5(a+b)(b-a+1)\,, \qquad (17)$$

therefore for Eq. (16) we obtain

$$g'_{32}(k) = (S_{N-k}^{N-2})/(2.N^2) = 0{,}25(2N-2-k)(k-1)/N^2 . \quad (18)$$

Then the normalized third order spectrum in a channel numbered by k, resulting from the convolution of $g_{22}(f_{x2})$ with $f_{x2} < 0$ and $g_1(f)$ with $f > 0$, will be:

$$g''_{32}(k) = g''_{32}(f_{x2}) = (S_{k-1}^{N-2})/(2N^2) = \\ = 0{,}25(N-3+k)(N-k)/N^2 , \quad (19)$$

where S_{k-1}^{N-2} is the sum of the terms of the arithmetic progression from $(k-1)$ to $(N-2)$.

In this case it is evident that for the work frequency range the value of k should be within the limits from 1 to $(N-1)$.

Accordingly, from Eqs. (18) and (19) the target normalized third order spectrum will be

$$g_{32}(k) = g'_{32}(k) + g''_{32}(k) = \left(S_{N-k}^{N-2} + S_{k-1}^{N-2}\right)/\left(2N^2\right) = \\ = 0{,}5\left(N^2 - 5N - 2k^2 + 2k(N+1) + 2\right)/N^2 . \quad (20)$$

The operating frequency range corresponds to a value of k from 1 to N.

The consecutive convolution of the other two components $g_{23}(f_{x3})$ and $g_{21}(f_{x1})$ with $g_1(f)$ is expressed by

$$g_{31}(k) = g_{33}(k) = 0{,}25 g_{32}(k) . \quad (21)$$

From Eqs. (20) and (21) it follows that the full normalized third order spectrum will be

$$g_3(k) = g_{31}(k) + g_{32}(k) + g_{33}(k) = \\ = 0{,}75 \frac{N^2 - 5N - 2k^2 + 2k(N+1) + 2}{N^2} . \quad (22)$$

Thus, by substituting Eq. (22) in Eq. (9) for $A_{TD}(k)$ we get:

$$A_{TD}(k) = A_{NL} - 10\lg\left(0{,}75 \frac{N^2 - 5N - 2k^2 + 2k(N+1) + 2}{N^2}\right) . \quad (23)$$

The dependency shown in fig. 3 is drawn from the analytically obtained expression Eq. (23). It is shown for three different values of the number of the channels N with A_{NL} = 26,7*dB* (depending on the parameters of the optical amplifier).

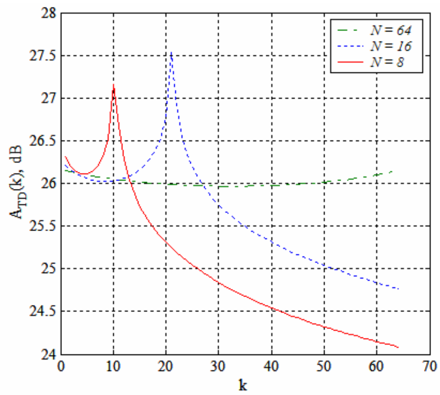

Fig. 3. Signal protectability from transient distortions as a function of the number of channels in a single optical amplifier

As is evident from fig. 3 the minimum of $A_{TD}(k)$ is obtained for the channel with number $k = (N+1)/2$ for odd values of N. Theoretically if N is even, the minimum of $A_{TD}(k)$ will be for two channels with numbers $k = N/2$ and $k = (N/2) + 1$. It is assumed that estimations according an average number of the channel are conditionally written as k_{av}.

Then the value of the signal protectability from transient distortions will be

$$A_{TDav} = A_{NL} + 1{,}25 - \\ - 10\lg\left(\frac{N^2 - 5N - 2k_{av}^2 + 2k_{av}(N+1) + 2}{N^2}\right), \quad (24)$$

where the value *1,25dB* is the increment of signal protectability from transient distortions due to the expansion of the normalized third order spectrum in the non-operative frequency bands situated to the left or right of the operating range. In this way part of the composite distortions and noises are filtered through the transparency window of the optical fiber. Therefore, the maximum value $A_{TD}(k)$ is reached at $k = 1$ and $k = N$.

B. Estimation of signal losses due to transient distortions in function of the number of amplifying sections

The value of the losses due to the non-linear transient distortions in m number of optical amplifiers can be obtained by means of the following equivalent formula

$$\Delta A_{TD_E}(m) = -20\lg(1 - 10^{-0{,}05 A_{TDOA}(m)}) . \quad (25)$$

In order to estimate $A_{TD\,OA}(m)$, it could be assumed that the level of signal at the output of each amplifying section (fig. 4) drops by $\Delta\alpha$, and the level of all third order non-linear products (which generate transient distortions in narrowband devices such as optical amplifiers) decreases by $3\Delta\alpha$.

Accordingly, if there is a defined signal level diagram (where p_S is the signal level in the transmission line), the signal protectability is increased by in every following amplifying section. In this way if the signal protectability from nonlinear transient distortions at the output of the first optical amplifier is A_{NL}, at the output of the second optical amplifier the signal protectability will be $A_{NL} + 2\Delta\alpha$, at the output of the third optical amplifier: $A_{NL} + 4\Delta\alpha$, and at the output of the m-th optical amplifier: $A_{NL} + 2(m-1)\Delta\alpha$.

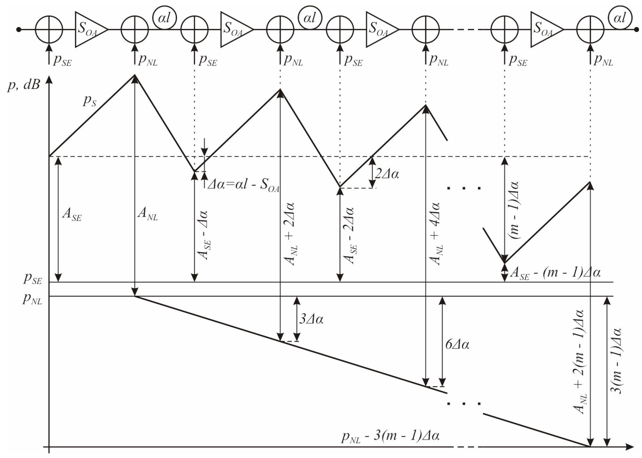

Fig. 4. Signal protectability diagram: A_{SE} – from spontaneous emitting, A_{NL} – from transient noise

The value of equivalent signal protectability from transient distortions when the number of optical amplifiers is m will be:

$$A_{NL}(m) = -10\lg(10^{-0,1A_{NL}} + 10^{-0,1(A_{NL}+2\Delta\alpha)} + .. + 10^{-0,1(A_{NL}+2(m-1)\Delta\alpha)}) =$$
$$= A_{NL} - 10\lg(1 + 10^{-0,1.2\Delta\alpha} + 10^{-0,1.4\Delta\alpha} + ...10^{-0,1.2(m-1)\Delta\alpha}) = \quad (26)$$
$$= A_{NL} - 10\lg S_G,$$

where $S_G = \dfrac{1-10^{(-0,2.m\Delta\alpha)}}{1-10^{(-0,2.\Delta\alpha)}}$ is the sum of terms of the geometric progression.

Taking into account Eq. (26), $A_{TD\ OA}(m)$ estimated for the middle channel will be

$$A_{TD\ OA}(m) = A_{NL}(m) + 1,25 -$$
$$-10\lg\left(\frac{N^2 - 5N - 2k_{av}^2 + 2k_{av}(N+1) + 2}{N^2}\right), dB \quad (27)$$

Therefore the value $A_{TD_E}(m)$ for the middle channel will be obtained by means of substitution of Eq. (27) in Eq. (25).

Based on the analytically obtained expressions Eqs. (27) and (25) in fig. 5 is shown the dependence of losses caused by transient distortions as a function of the number of optical amplifiers. It is shown for the middle channel for three values of N when A_{NL} = 26,7*dB* (depending on the parameters of the optical amplifier) and $\Delta\alpha$ = 0,3 (depending on the parameters of the optical amplifier and optical fiber).

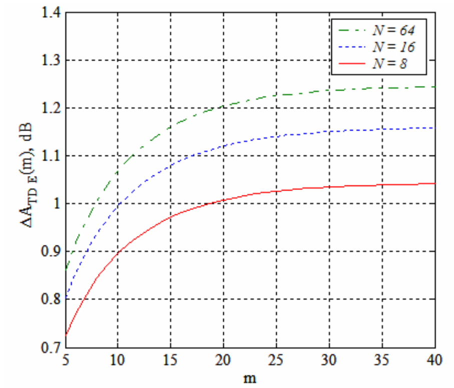

Fig. 5. Losses due to nonlinear transient distortions as a function of the number of optical amplifiers

C. Estimation of the signal level due to intersymbol distortions in function of the number of amplifying sections

Intersymbol distortions decrease the range of the eye-diagram $(1 - K_{ISD_U})$ times. The value of intersymbol distortion ratio multiplied by the voltage at the input of the electronic amplifier is:

$$K_{ISD_U} = \left(K_{ISD_{mE}}\right)^{0,5}, \quad (28)$$

where $K_{ISD_{mE}} = K_{ISD_{mO}} = \left(10^{-0,14A_{ISD}(m)}\right)$ is the transient distortions ratio according electrical (for the input of the electronic amplifier) and optical power (for the transmission line).

Thus as is the case with signal losses due to transient distortions, the signal losses due to intersymbol distortions in the transmission line will be

$$\Delta A_{ISD}(m) = -20\lg(1 - 10^{-0,05A_{ISD}(m)}), \quad (29)$$

where $\Delta A_{ISD}(m) = 41/(1 + 10^{-7}l^2m^2)$ s signal protectability from inter-symbol distortions caused by dispersion distortions inside the optical fiber; $l = (\Delta\alpha + S_{OA})/\alpha$ (l – is the length of amplifying section, α – is the kilometric attenuation ratio of optical fiber, S_{OA} – amplification of optical amplifier in the transparency window, $\Delta\alpha$ – is the difference between attenuation in an amplifying section with length of *1km* and the amplification of the optical amplifier

III. Conclusion

The approach with dividing losses into dependent on and independent from the number of amplifying sections leads to substantial simplification of the assigned task. This solution is based on the physical characteristics of the transmission line (which depend on the type of optic fiber) and the physical characteristics of transmitting and receiving optical module, multiplexers and demultiplexers.

In this paper we propose an approach for estimating only losses from transient and intersymbol distortions in hybrid television network. Estimating the difference between the maximum possible and total of real signal losses given at the EAI and the maximum signal level in the transmission line, taking into consideration the losses in the termination devices is also associated with the need of complete analysis of losses due to all kinds of additive noise and the signal losses due to signal fading in the transmission line. This complete analysis would allow estimation of optimum number of amplification sections and appears as a goal of an ongoing research.

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