Estimating the Number of Amplifying Sections in Hybrid Fiber-Coaxial Television Network Using an Iterative Approach

Krasen K. Angelov[1], Kiril K. Koitchev[2],
Nataliya A. Varbanova[3], Stanimir S. Sadinov[4]

Abstract – **The number of amplifying sections of hybrid fiber-coaxial (HFC) network is causally related to amplitude losses, dispersive expansion of code pulses and nonlinear distortions. Since all parameters are correlated, an iterative approach for estimating the number of amplifying sections in an optical trunk line is proposed. Total signal losses are estimated and through series of iterations a solution is found which for a given number of amplifying sections for the current iteration will yield minimum relative percentage error.**

Keywords – **optical trunk line, optical amplifier, signal level, nonlinear distortion**

I. Introduction

The modern hybrid cable TV networks use as backbone network high speed optical trunk-lines. The power potential of the system is used to determine the optimum number of amplifying sections in certain optical trunk-line. It is equal to the difference between the maximum possible signal level and the signal losses in the transmission line and termination devices. These are amplitude losses, the losses due to transient and intersymbol distortions plus additive noise losses. Proposal of a practical approach for determining the number of amplifying sections depending on the physical parameters of the transmission line and used optical equipment has been the aim of this work.

The main factors are the physical parameters of optical amplifiers and optical transmission and receiver module. [2,4]. A transmission line can be rendered as consecutively connected amplifying sections [5] each of which can be modeled as per the block diagram in Fig. 1.

In Fig. 2 and 3 are shown substitution models of optical transmission and receiver modules.

[1]Krasen Angelov is with the Faculty of Electrical Engineering and Electronics, Technical University – Gabrovo, 4 H. Dimitar St., 5300 Gabrovo, Bulgaria, E-mail: kkangelov@dir.bg

[2]Kiril Koitchev is with the Faculty of Electrical Engineering and Electronics, Technical University – Gabrovo, 4 H. Dimitar St., 5300 Gabrovo, Bulgaria, E-mail: koitchev@tugab.bg

[3]Nataliya Varbanova is with the Faculty of Electrical Engineering and Electronics, Technical University – Gabrovo, 4 H. Dimitar St., 5300 Gabrovo, Bulgaria, E-mail: nataliavarbanova@abv.bg

[4]Stanimir Sadinov is with the Faculty of Electrical Engineering and Electronics, Technical University – Gabrovo, 4 H. Dimitar St., 5300 Gabrovo, Bulgaria, E-mail: murry@tugab.bg

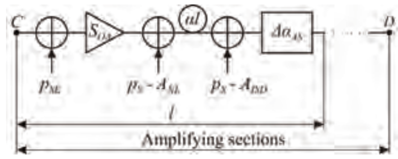

Fig. 1. Structural diagram of amplifying sections

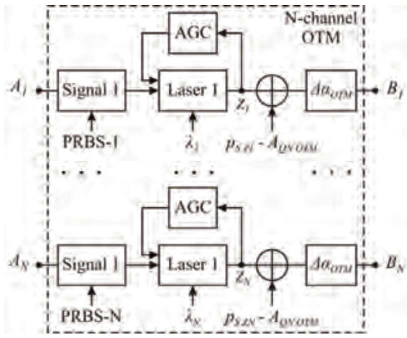

Fig. 2. Structural diagram of optical transmission module

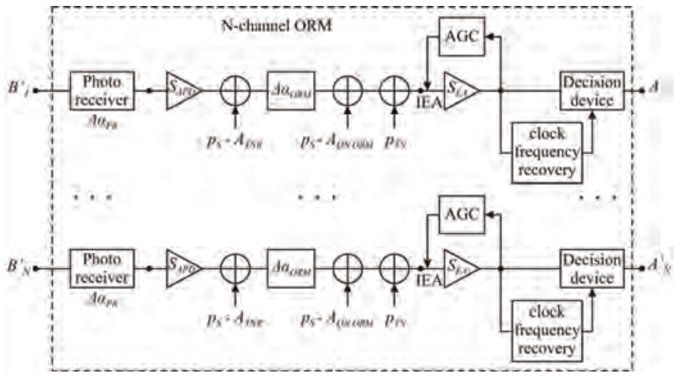

Fig. 3. Structural diagram of optical reception module

The basic parameters characterizing the optical transmission module (OTM) are as follows:

– absolute signal level at the laser output in point Z_i: $p_{S\,Zi}$;

– additional amplitude losses due to inaccuracy of AGC, degradation of laser in time and its thermal instability, the type of linear code and energy losses during its input in the fiber: $\Delta\alpha_{OTM}$;

– signal protectability from laser quantum noise: $A_{QN\,OTM}$.

The basic parameters characterizing optical receiver module (ORM) are:

– attenuation of photo-receiver: α_{PR};

– amplification of avalanche photo-diode S_{APD};

– signal protection from photo-receiver quantum noise: $A_{QN\ ORM}$;
– noise figure of electronic amplifier (EA): *NF*;
– additional signal amplitude losses due to inaccuracy of AGC, instability of the decision device threshold level due to phase distortions of the clock frequency divider, and due to the energy losses at the optical receiver module input plus other factors: $\Delta\alpha_{ORM}$;
– signal protectability from intersymbol distortions generated by the limited frequency band of the signal of the electronic amplifier: $A_{ISD}(0)$.

Optimum number of amplifying sections in the optical trunk lines of HFC network can be determined by means of iterative approach. By applying iterative cycle it is possible to search for such a solution which, given the number of amplifying sections m_j for the current iteration, will yield relative percentage error that satisfies the inequality

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

where $\Delta A_E(m_j)$ is the difference between the maximum possible and the total real signal losses given for the input of the electronic amplifier (IEA) (see Eq. 2); $A_{N_E}(m_j)$ – is the minimum permissible signal level (see Eq. 18). Consequently, this is a strict criterion which demands that the minimum permissible signal level at the IAE should be 10 times higher than the level of the relative signal percentage losses.

The difference between maximum possible losses and the total real signal losses given at the IEA is shown in [1]:

$$\begin{aligned}\Delta A_E(m) = A_{\max_E}(0) - \Delta A_{S_E}(m) - \Delta A_{TD_E}(m)\\ - \Delta A_{ISD_E}(m) - \Delta A_{AN_E}(m) - A_{N_E}(m) \ge 0\end{aligned} . \tag{2}$$

A complete analysis of Eq. 2 requires determination of all input components in the expression. In [1] has been shown the determination of two of the components in Eq. 2 – i.e the losses due to transient $A_{TD}(m)$ and inter-symbol distortions $\Delta A_{ISD}(m)$ in transmission line. Here will be considered the determination of the other terms: $A_{\max_E}(0)$ – the energy potential of the system, $\Delta A_{S_E}(m)$ – signal amplitude losses, and $\Delta A_{AN_E}(m_j)$ – and additive noise losses.

Calculations for signal losses are to be performed for the electronic amplifier input (Fig. 1), therefore the index "E" is introduced.

The solution of the problem is reduced to determining the number of amplifying sections *m* according to permissible signal losses due to transient and intersymbol distortions. This solution is used as boundary condition at the second more complex iterative solution for determining the number of amplifying sections according to total losses.

II. DETERMINING THE NUMBER OF AMPLIFYING SECTIONS m_0 ACCORDING TO THE PERMISSIBLE SIGNAL LOSSES

To ensure reliable performance of the decision device, the signal protectability from its pertaining transient and inter-symbol distortions should be greater than or equal to 6*dB* [3]. Accordingly, the sum of total losses in this particular case should not exceed *6dB*:

$$\Delta A_{TD_E}(m_0) + \Delta A_{TD_E}(0) + \Delta A_{ISD_E}(m_0) + \Delta A_{ISD_E}(0) \le 6dB . \tag{3}$$

To simplify the solution in Eq. 3 it is possible to apply two equal conditions taking into account its monotony:

$$\Delta A_{TD_E}(m_0) \le 3 - \Delta A_{TD_E}(0) = \Delta A_{TD\,AV} , \tag{4}$$

$$\Delta A_{ISD_E}(m_0) \le 3 - \Delta A_{ISD_E}(0) = \Delta A_{ISD\,AV} , \tag{5}$$

where $\Delta A_{TD\ AV}$ are permissible threshold values of signal protectability losses generated by the transient distortions in the transmission line, $\Delta A_{ISD\ AV}$ is the permissible value of signal losses due to the intersymbol distortions [1].

Drawing upon these relationships and those found in [1] it is possible to formulate the following analytical expressions for estimating the number of amplifying sections, depending on the transient and intersymbol distortions:

$$m'_0 \le INT\left[\frac{-5\lg\left(\left(1-10^{0,1(A_{NL}+1,25)}\right)\left(1-10^{-0,2\Delta\alpha}\right)\left(1-10^{-0,05\Delta A_{TD\,AV}}\right)^2\right)}{\Delta\alpha}\right] \tag{6}$$

$$m''_0 \le INT\left[\frac{\left(10^7 \dfrac{41}{\left(-20\lg\left(1-10^{-0,05\Delta A_{ISD\,AV}}\right)\right)-1}\right)^{0,5}}{l}\right] . \tag{7}$$

where $A_{NL} = 10\lg\left(\left(NC_1P_S\right)/\left(N^3C_3P_S^3\right)\right)$ is the group signal protectability resulting from the total power of nonlinear transient distortions (*N* – number of channels at the optical amplifier output, NC_1P_S и $N^3C_3P_S^3$ – are the power rates of the transient distortion signal at the optical amplifier output, C_1 and C_3 – coefficients of decomposition of optical amplifier output power in the order determined by the levels of input power), $\Delta\alpha$ – difference between the amplitude losses in the amplifying section of length equal to *1km* and the am-plification of the optical amplifier. If in Eq. 6 the value under the logarithm sign is negative then it follows that $m'_0 \to \infty$.

After determining the number of amplifying sections according Eqs. 6 and **7**, the value m_0 should be selected from the lower one between m'_0 and m''_0. In the second part of the solution m_0 is used as initial limit value at first iteration.

III. DETERMINING THE NUMBER OF AMPLIFYING SECTIONS m_j BY THE TOTAL SIGNAL LOSSES

Initially it is necessary to determine the unknown terms from Eq. 2.

A. Estimation of the energy potential of the system $A_{\max_E}(0)$

$A_{\max_E}(0)$ characterizes the energy potential of the system which is necessary to calculate the length of the amplifying section. He is equal to the difference between the maximum possible signal protectability $A_{\max E}$ (in each channel) of the optical system and the sum of signal losses generated in the termination devices i.e. he does not depend on the number of amplifiers *m*. Consequently the maximum possible signal level $A_{\max_E}(0)$ will be determined by

$$A_{\max_E}(0) = A_{\max_E} - \left[\Delta A_{S_E}(0) + \Delta A_{TD_E}(0) + \Delta A_{ISD_E}(0)\right], \qquad (8)$$

The first term in Eq. 8 depends on the physical characteristics of the transmitter and the receiver module

$$A_{\max_E} = 2p_{S\,Z1} + S_{APD} - \alpha_{PR} - p_{TN}\ , \qquad (9)$$

where $p_{TN} = 10\lg\left(kT\Delta f NF/1mW\right)$ is the level of thermal noise at the input of the electronic amplifier ($k = 1{,}38.10^{-23}$ is the constant of Boltzmann, T – absolute temperature, $\Delta f = f_{T1}$ – frequency band equal to the signal clock frequency for a single channel, NF – amplifier noise figure).

The second term in Eq. 8 reflects signal losses due to atenuation in termination optical devices (optical transmission module and multiplexer/demultiplexer) and is determined by

$$\Delta A_{S_E}(0) = 2\left(\Delta\alpha_{OTM} + \alpha_M + \Delta\alpha_M + \alpha_D + \Delta\alpha_D\right) + \Delta\alpha_{ORM}\ , \qquad (10)$$

where α_M, α_D – attenuation in multiplexer/demultiplexer, $\Delta\alpha_{OTM}$, $\Delta\alpha_M$, $\Delta\alpha_D$, $\Delta\alpha_{ORM}$ – variation in attenuation of optical transmission module, multiplexer/demultiplexer and the optical receiver module. It is evident that all parameters depend on the physical characteristics of the optical equipment.

The third and fourth terms in Eq. 8 are determined by Eqs. 4 and 5 [1].

Therefore, by substituting Eqs. 4, 5, 9 and 10 in Eq. 8 can be determined $A_{\max_E}(0)$.

B. Calculation of losses generated by signal attenuation

Signal losses due to attenuation in the amplifying section $\Delta A_{S_E}(m_j)$ are determined by the physical characteristics of the used fiber and the amplification of the optical amplifiers

$$\Delta A_{S_E}(m_j) = 2\Delta A_{S_O}(m_j) = 2m_j\Delta\alpha\ , \qquad (11)$$

where $\Delta\alpha$ is the difference between the attenuation in the amplifying section of length equal to *1km* and the amplification of the optical amplifier [1]. It is evident from Eq. 11 that these losses will have linear increment with the rise of number of amplification sections.

C. Calculation of losses generated by additive noises

The real signal protectability losses $\Delta A_{AN_E}(m_j)$ generated by additive noises consist of two components

$$\Delta A_{AN_E}(m_j) = A_{TNR}(m_j) - A_{AN_E}(m_j)\ , \qquad (12)$$

where $A_{TNR}(m_j)$ is the real value of signal protectability from thermal noises (which accounts and signal attenuation in the transmission line), $A_{AN_E}(m_j)$ – equivalent signal protectability from additive noises at the IEA:

$$A_{TNR}(m_j) = A_{\max_E}(0) - \Delta A_{S_E}(m_j)\ , \qquad (13)$$

$$A_{AN_E}(m_j) = -10\lg\left(10^{-0{,}1A_{QN\,OTM}} + 10^{-0{,}1A_{QN\,ORM}} + 10^{-0{,}1A_{SE}(m_j)} + 10^{-0{,}1A_{TNR}(m_j)}\right), \qquad (14)$$

Eq. 14 accounts the influence of $A_{QN\,OTM}$ and $A_{QN\,ORM}$, which stand for signal protectability from laser quantum noise in the transmission optical module and the photo-receiver in the optical receiver module as well as the signal protectability from spontaneous emissions $A_{SE}(m_j)$.

$A_{QN\,OTM}$ and $A_{QN\,ORM}$ are determined by the physical characteristics of the optical transmitter and receiver. $A_{SE}(m_j)$ at the input of the first optical amplifier is determined by

$$A_{SE} = p_{S\,Zi} - \Delta\alpha_{OTM} - \Delta\alpha_M - \alpha_M - p_{SE}\ , \qquad (15)$$

The level of spontaneous emission at the input of the first optical amplifier for wavelength $\lambda = 1550nm$ in the frequency band from *0* to f_{T1} is the same and equal to

$$p_{SE} = 10\lg\frac{h.\nu.f_{T1}.K_{SE}}{1mW} = -158 + 10\lg f_{T1} + 10\lg K_{SE}\ , \qquad (16)$$

where f_{T1} is the clock frequency, $h = 6{,}62.10^{-34}\ J.s$ – the constant of Plank, $\nu \approx 2.10^{14}\ Hz$ – spontaneous emission frequency, K_{SE} – spontaneous emission coefficient, *–158,9dB* is the absolute level of spontaneous emission for *1Hz* at $K_{SE} = 1$.

The level of spontaneous emission at the input of every other optical amplifier decreases by $\Delta\alpha$. At the input of the second optical amplifier it has the value $A_{SE} - \Delta\alpha$ and at the input of the *m*-th optical amplifier: $A_{SE} - (m-1)\Delta\alpha$. Consequently by accounting the addition of the spontaneous emission [3] from every optical amplifier, the equivalent signal protectability will be of the kind

$$\begin{aligned} A_{SE}(m) &= -10\lg(10^{-0{,}1A_{SE}} + 10^{-0{,}1(A_{SE}-\Delta\alpha)} + 10^{-0{,}1(A_{SE}-2\Delta\alpha} + \ldots \\ &\quad + 10^{-0{,}1(A_{SE}-(m-1)\Delta\alpha)}) = \\ &= A_{SE} - 10\lg(1 + 10^{0{,}1\Delta\alpha} + 10^{0{,}1.2\Delta\alpha} + \ldots + 10^{-0{,}1(m-1)\Delta\alpha}) = \\ &= A_{SE} - 4{,}34\ln S'_G \end{aligned}, \qquad (17)$$

with a sum of the terms of the geometrical progression $S'_G = \frac{10^{0,1m\Delta\alpha}-1}{10^{0,1.\Delta\alpha}-1}$.

D. Calculation of $A_{N_E}(m_j)$

Minimum permissible signal level at the IEA (used in Eq. 1) is determined by

$$A_{N_E}(m_j) = 9 + 10\lg H^2 = 20\lg(U_S/\sigma_N)\,, \qquad (18)$$

where $H = 0{,}25\sqrt{2}(U_S/\sigma_N)$ (U_S – voltage at the IEA, σ_N – root mean square voltage of the additive noise in relation to the IEA, therefore U_S/σ_N is signal-to-additive noise ratio at the IEA).

The value of $A_{N_E}(m_j)$ is connected with the requirement for error probability in the electronic decision device $P_e \le mlP_{km}$, where P_{km} and l are kilometric error probability (usually 10^{-13}) and length of amplifying sections and are known from the input parameters.

Based on the relationships drawn in [1] and relationships in Eqs. 12 to 17 it is possible to draw a graph of the variation in losses generated by transient and intersymbol distortions plus the losses from additive noises as function of the number of amplifying sections. In Fig. 4 is shown a graphic relationship with the following physical parameters of the optical equipment: *Δα = 0,3dB*, eight-channel system and optical amplification *20dB*.

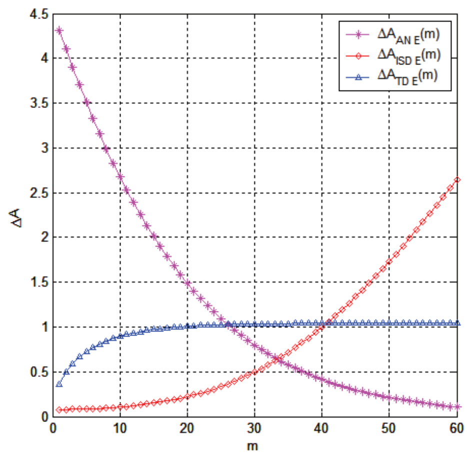

Fig. 4. Losses due to transient, intersymbol distortions and additive noises as function of the number of amplifying sections

From Fig. 4 it is evident that with small number of amplifying sections there is a substantial influence of additive noise losses whereas with the increase of the number of amplifiers – of the losses due to intersymbol distortions. The area closed by the three graphs determines the number of amplifying sections by the criteria of transient and inter-symbol distortion losses and additive noise losses. Proportionally increasing losses due to signal attenuation along the fiber should also be added and the other terms in Eq. 2 are to be accounted for as well.

E. Evaluation of δ_{Cj} in determining m_j by total signal losses

After all terms have been determined in Eq. 2 and in order to determine Eq. 1, it is necessary to calculate $\Delta A_E(m_j)$ according to Eq. 2.

By substituting Eqs. 2 and 18 in Eq. 1, there should be checked whether *j*-th step of iteration from the calculations for m_j gratifies Eq. 1. Provided $\Delta A_E(m_j) \le 0$ then in the next *(j+1)*-th iteration *m* should be decreased (i.e. $m_{j+1} < m_j$) and all calculations repeated in order to determine δ_{Cj+1}. If $\Delta A_E(m_j) > 0$, but Eq. 1 is not gratified then in the next *(j+1)*-th iteration *m* should be increased (т.е. $m_{j+1} > m_j$).

Sequential iterations are applied unless the condition of Eq. 1 is fulfilled. Consequently the final result for the number of amplifiers (amplifying sections) will gratify limitations imposed by the total signal losses in assuring respective quality factors of the transmitted signals.

IV. Conclusion

The following conclusions could be drawn:

- The characteristics of the transmission line depend on the type of fiber whilst the signal amplification depends on the characteristics of the optical transmission and receiver module plus the multiplexer/demultiplexer. These characteristics have their impact while determining the number of amplifying sections and, accordingly, are included in the content of the analytical expressions.
- The iterative approach allows optimal determination of the number of amplifying sections based on two principal criteria: the losses generated by transient and intersymbol distortions and the total losses.
- The proposed approach is applicable i.e. it is based on the physical characteristics of the used optical equipment.

References

[1] K. Angelov, K. Koitchev, N. Varbanova, Estimating losses from transient and intersymbol distortions in hybrid fiber-coaxial television network, ICEST 2009, Proc. of Papers Vol. 1, pp.113-116, Sofia, Bulgaria, 2009.

[2] K. Angelov, K. Koitchev, S. Sadinov, An Investigation of Noise Influences in Optical Transmitters and Receivers in Cable TV Networks, ICEST 2006, Proc. of Papers, pp.102-105, Sofia, Bulgaria, 2006.

[3] R. Freeman, Fiber-Optic Systems for Telecommunications, John Wiley & Sons, New York, 2002.

[4] Л. Йорданова, В. Топчиев, Оптимизиране на параметрите на усилватели, използвани в оптичния канал на CATV системи, TELECOM 2008, стр. 206-211, Варна, 2008.

[5] О. Панагиев, Определяне на оптималния брой на последователно свързани усилватели в широколентова кабелна комуникационна мрежа. TELECOM 2008, стр. 255-260, Варна, 2008.