Limitations in the Design of CATV Fiber-Optic Links

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Abstract – **In the paper the results of an investigation in the field of CATV system design are discussed. They refer to the system's optical lines in particular, when attenuation, dispersion and non-linear effects in the chosen fiber are taken into consideration. Criteria based on the bit rate and RF band transmitted are suggested to determine the maximum length of an optical line with no additional signal amplification provided. Relations are given to evaluate the influence of both the scattering effects and the self- and cross-phase modulation on the maximum launch power that provides the desired quality of information received.**

Keywords – **CATV system, Fiber-optic link, Dispersion, Scattering and Kerr effects, Receiver sensitivity.**

I. Introduction

The main trends in CATV system development are closely related to digital and fiber-optics technologies whose application is constantly gaining ground. Modern CATV systems are of a hybrid (fiber/coaxial) type, the system's main part implementing fiber optics and the peripheral one – coaxial cables. To increase the transport capacity of the system a dense wavelength division multiplexing (DWDM) technology is employed that results in a multiple usage of the radio frequency (RF) band allocated for interactive upstream and downstream channels [1].

The systems here considered differ by using RF carriers to transmit the information signals. Two frequency bands are provided for signal transmission from the headend to the subscribers: 112 MHz to 550 MHz (for analog video broadcasting) and 550 MHz to 862 MHz (for narrow casting services – data, voice and digital video). Analog video signals are transmitted by using VSB-AM while QAM methods (usually 256-QAM) are mainly used to transmit digital video programs and data. The system reverse paths make use of the 5 MHz to 65 MHz frequency band and subscribers' signals are transmitted by using QPSK or 16-QAM methods. The RF signals are transferred over the optic fiber by means of optic carriers whose wavelength may be 1310 nm or 1550 nm while with DWDM the wavelengths can be chosen from the wave range recommended by ITU.

The parameters of the signals transmitted over optic fibers are worsening due to attenuation, dispersion and non-linear effects. These effects set some limitations on the RF signal bandwidth/bit rate, the maximum optic-fiber length allowed, the laser output power, the DWDM channel separation etc. When designing the optical part of a HFC system the dependences of the system parameters on the optic fiber parameters must be known. The paper is aiming at analyzing that kind of a problem.

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II. System's Configuration and Parameters of its Components

The block-diagram of a multimedia CATV system to be designed is shown in Fig. 1. A specific feature of the system is that it implements DWDM technology to transmit interactive downstream channels from headend to hub over one optical fiber. The same technology is applied in multiplexing the upstream channels that transmit signals from subscribers to headend. Eight wavelengths ($\lambda_2 \ldots \lambda_9$) selected from the ITU grid are used to transmit 256-QAM signals for the interactive subscribers' service. The system here considered operates in the C band (from 1536.61 nm to 1560.61 nm) and the channel spacing selected is 1,6 nm (200 GHz). The RF signals of the analog TV programs (VSB-AM signals) are transmitted over a separate fiber and to this end they modulate an optical carrier of wavelength λ_1 = 1550 nm.

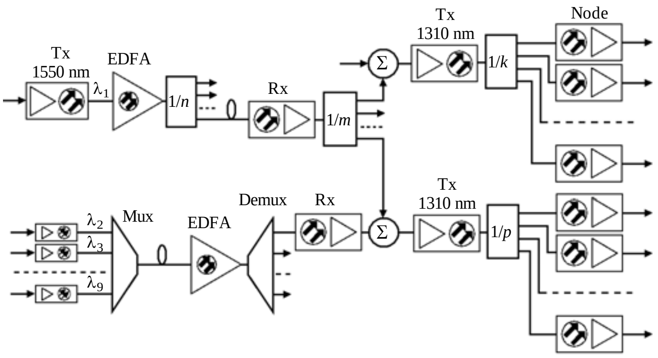

Fig. 1 System's configuration

The analog transmitter and the ITU transmitters in the headend can be regarded as externally modulated sources that comprise a distributed-feedback (DFB) laser coupled to a Mach-Zehnder modulator. Outputs from the ITU transmitters are multiplexed and transported to the hub. To compensate for the loss within the optical channel erbium-doped fiber amplifier (EDFA) is used. In the hub the demultiplexed optical signals are routed to receivers. Outputs of the receivers are passband filtered, and then routed to the proper 1310 nm transmitter. Combined at RF, both analog and QAM signals drive the laser. At the node a single detector converts these signals to RF for distribution into the plant [2].

When a frequency band of 300 MHz is provided for narrowcasting 256-QAM channels the bit rate turns out to be about 2 Gbit/s. Since the broadcast analog spectrum is gradually reduced and the narrowcast one is increased even higher bit rates (up to 5 Gbit/s) can be attained if the entire 112 to 862 MHz band is used. As for the bit rate over the reverse path it turns out to be lower due to its narrower frequency band, from one side, and to signal transmission based on modulation methods of smaller band efficiency, from the other side. Hence, a maximum bit rate of 5 Gbit/s is taken for granted when designing the optical lines.

In the design of optic lines the parameters of the following devices have been used:

Externally modulated transmitter: Output 0 dBm;
Optical receiver: Sensitivity –18 dBm;
DWDM (De)Multiplexer: Insertion loss 5.5 dB;
EDFA: Gain 23 dB, Maximum Output 17 dB;
Connector: Insertion loss 0.9 dB.

Two types of fiber have been chosen to build up the system's optical lines – S-SMF and NZ-DSF of the Sterlite Optical Technologies Ltd. The S-SMF chosen is designed to work within the wavelength range 1310-1600 nm and its parameters at 1550 nm are as follows: $\alpha = 0.22$ dB/km, MFD = 10.5 μm, $D_{ch} = 17$ ps/nm.km, $D_{pm} \leq 0.2$ps/√km. The parameters of the chosen NZ-DSF are as follows: $\alpha = 0.22$ dB/km, MFD = 9.6 μm, $D_{ch} = 2.0$ to 6.0 ps/nm.km at 1530 – 1565 nm, $D_{pm} \leq 0.2$ps/√km.

III. LIMITATION OF THE MAXIMUM FIBER LENGTH DUE TO DISPERSION

Chromatic dispersion (CD) and polarization mode dispersion (PMD) are the two main sources of dispersion in the single-mode optical fibers. The first one is due to frequency dependence of the fiber refractive index $n(\omega)$. The velocity of the light wave within the fiber being $v = c/n(\omega)$, the spectral components of the transmitted pulse do travel at different velocities and arrive at the fiber end at different times, thus causing some pulse broadening. PMD takes place when the fiber core is not perfectly circular (which causes the two polarizations of light to travel at different velocity). The different arrival times of the two polarizations will cause the pulse to broaden in a similar way as CD does.

The total pulse spreading due to CD and PMD is given by

$$\Delta\tau_D = \sqrt{\tau^2 - \tau_0^2} = \left|\Delta\tau_{ch}\right| + \Delta\tau_{pm} = D_{ch}\Delta\lambda_{Ls}L + D_{pm}\sqrt{L}\,, \qquad (1)$$

where: τ_0 and τ is the optical pulse width at the fiber input and output respectively; $\Delta\tau_{ch}$ and $\Delta\tau_{pm}$ is the pulse spreading due to CD and PMD respectively; D_{ch} and D_{pm} are the dispersion coefficients; $\Delta\lambda_{Ls}$ is the spectral width of the laser and L is the fiber length. Dispersion-induced broadening of the pulses is undesirable since it interferes with the detection process thus leading to errors in the received bit pattern. Hence, it is obvious that CD and PMD do limit the bit rate (BR) and transmission distance (L) of the system.

The signal data rate can be limited by dispersion when the pulse spreading becomes a significant portion of the bit period. Such a spreading affects the bit error rate (BER) at the receiver because the pulses interfere with each other thus creating noise known as inter-symbol interference. The penalty to the carrier-to-noise ratio (CNR) at the receiver can be quantified by means of a number of methods.

In the paper the quarter-bit interval equation [3] is applied to evaluate the maximum fiber length $L_{\max}$ limited by dispersion. It imposes that the rms value of the pulse spreading do not exceed a quarter of the bit interval, i.e. $\Delta\tau_D/\sqrt{2} \leq T/4$, where $T = 1/BR$. Hence,

$$L_{\max} = \frac{\sqrt{2}}{4D_{ch}\left(\Delta\lambda_{Ls}\right)BR}\,, \qquad (2)$$

the typical spectral width of a high-quality DFB laser diode being $\Delta\lambda_{Ls} = 0.1$ nm. It is assumed that no power penalty due to PMD will be incurred by the system if

$$\Delta\tau_{pm} = D_{pm}\sqrt{L} < \frac{0.1}{BR}\,. \qquad (3)$$

With $D_{pm} = 0.2$ ps/√km and $BR = 5$ GHz the above requirement is met for $L \leq 10\,000$ km, i.e. PMD will not affect the parameters of the CATV system.

In the case the values of the maximum fiber length as limited by CD for two types of optic fiber chosen for the system under consideration are: 40 km (S-SMF) and 160 km (NZ-DSF). Therefore the NZ-DSF fiber has been used in the optical line between the headend and the hub. The S-SMF fiber is more acceptable for reverse path where the maximum bit rate is below 1 Gbit/s.

IV. CONDITIONS TO AVOID UNACCEPTABLE WORSENING OF THE SYSTEM'S PARAMETERS DUE TO NON-LINEAR EFFECTS IN THE FIBER

Non-linear effects occur in fiber links when the transmitted power along the link reaches a threshold power. Two types of nonlinear effects can appear in the single-mode fibers usually applied in HFC CATV systems: scattering effects and Kerr effects. Stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) are associated with the first type. Three types of Kerr effects are considered to be important for modern optical communications: self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM). Since the fiber attenuation will diminish the power as it travels along the fiber, the non-linear effects take place over the effective length of the fiber L_{eff} given by the equation

$$L_{eff} = \left(1 - e^{-\alpha L}\right)\Big/\alpha \qquad (4)$$

where α is the fiber attenuation constant in 1/km and can be calculated by the following formula: $\alpha = 0.23\,\alpha$[dB/km]. Therefore for long link lengths and a fiber attenuation of 0.22 dB/km ($\alpha L >> 1$) $L_{eff} \approx 1/\alpha \approx 20$ km.

SRS and SBS are due to non-elastic interaction between the pump wave of wavelength λ_p and the fiber core that transfers most of the pump energy into a Stokes light wave of wavelength $\lambda_s > \lambda_p$. With a single optical channel the power scattering due to SBS and SRS results in decreasing the received optical power, on one hand, and in increasing the noise floor, on the other hand. In other words, CNR at the optical receiver input is reduced, thus causing the received signals quality to worsen. The maximum power that is launched into the fiber without causing unacceptable worsening of the signal quality because of the scattering effects is limited to a given threshold value.

The critical pump power required to reach the Brillouin threshold in a single-mode fiber with $\alpha L >> 1$ is given by [4]:

$$P_{th}\left(SBS\right) = 21kS_{eff}\Big/\left(g_B L_{eff}\right), \quad (5)$$

where k accounts for the relative polarizations of the interacting waves (the value of k lies between 1 and 2), g_B is the values of the Brillouin-gain coefficient at a Stokes frequency ω_s ($g_B \approx 5.10^{-11}$ m/W at a pump wavelength of 1550 nm), S_{eff} is the effective core area. Parameter S_{eff} can be calculated with formula $S_{eff} = \pi(\mathrm{MFD}/2)^2$. This makes $S_{eff} = 86.6\ \mu\mathrm{m}^2$ for the chosen type of S-SMF fiber and $S_{eff} = 72.4\ \mu\mathrm{m}^2$ for the chosen type of NZ-DSF fiber. The values obtained for P_{th} (SBS) are shown in Table 1.

The Raman-gain spectrum being very broad, SRS can cause problems in DWDM systems and does not affect the parameters of the single-channel systems. Due to SRS an energy transfer from lower channels (shorter wavelengths) to higher channels (longer wavelengths) is observed. This results in worsening the *CNR* in lower channels and limiting the transport capacity of CATV systems. The following relation can be used to calculate the maximum power per channel P_i in order to provide 1 dB power penalty [5]:

$$P_i N\left(N-1\right)\Delta\lambda_s L_{eff} < 40\,000\,[\mathrm{mW.nm.km}], \quad (6)$$

where N is the number of DWDM channels and $\Delta\lambda_s$ is the channel spacing. The results for P_i that refer to $N = 8$ and $\Delta\lambda_s = 1.6$ nm for the chosen fibers are shown in Table 1.

TABLE 1
LAUNCH POWER LIMITATIONS DUE TO NON-LINEAR EFFECTS

Fiber Type	P_{th} SBS dBm	P_i SRS dBm	P_{th} SPM dBm	P_i XPM dBm	P_{out}/P_{ijk} dB
S-SMF	5.8	13.5	17.2	5.4	91
NZ-DSF	4.8	13.5	16.4	4.6	76

SPM occurs when high intensities are launched into the transmission fiber, causing the index of refraction n to be slightly modified as a function of the optical intensity. Its magnitude can be defined by means of the intensity-dependent nonlinear phase shift of the optical field Φ_{NL}. The maximum phase shift occurs at the pulse center and is given by

$$\Phi_{NL\max}(\mathrm{SPM}) = \left(2\pi n^* L_{eff}\big/\lambda S_{eff}\right)P \;. \quad (7)$$

where n^* is the nonlinear index coefficient ($n^* \approx 3.2 \times 10^{-20}$ m^2/W). SPM is responsible for broadening the pulses spectrum. In order to avoid inadmissible intra-symbol distortion in the NRZ digital system the requirement $\Phi_{NL\max}(\mathrm{SPM}) \le \pi/2$ must be fulfilled. The condition is held when the maximum launch power is less than P_{th} (SPM) whose values are given in Table 1.

XPM appears when two or more waves propagate inside the fiber and interact between them in result of the nonlinearity of the refractive index produced by the total power along the fiber. This effect is similar to SPM but the phase shift of one channel depends on the power of other channels. The maximum phase shift due to XPM associated with the i-th channel ($i = 1,2, \ldots, N$) can be estimated by [4]

$$\Phi_{NL\max}(\mathrm{XPM}) = \left(2\pi n^* L_{eff}\big/\lambda S_{eff}\right)\left[P_i + 2\sum_{k\neq i}^{N} P_k\right]. \quad (8)$$

As seen from (10), XPM is always accompanied by SPM. If the optical fields are of equal intensity the XPM contribution to the nonlinear phase shift is twice as big as that of SPM. The maximum phase shift in a NRZ digital system becomes significant when $\Phi_{NL\max}$ (XPM) > $\pi/2$ i.e. in the same way as in the case with SPM.

In DWDM systems both SPM and XPM can cause significant phase changes that limit the system performance. If we take $\Phi_{NL\max}$ (XPM) = $\pi/2$ as an acceptable value, the power in each channel is restricted to

$$P_i \le \pi\left[2\gamma L_{eff}\,(2N-1)\right]^{-1}, \quad (9)$$

where P_i is the power assumed to be the same in each channel. The values of P_i calculated for $N = 8$ are given in Table 1 for the chosen type of fibers.

FWM is the interaction between three channels transmitted at different frequencies f_i, f_j and f_k, that results in a fourth product frequency $f_{ijk} = f_i + f_j - f_k$. FWM products reduce the energy in the transmitted channels, thus causing CNR to decrease at the receiver input. In addition, if the resulting frequency product is within the bandwidth of the transmitted channel it will cause crosstalk at the receiver.

The following formula [6] can be used to evaluate the output power of the FWM product, generated at optical frequency f_{ijk} due to the interaction of signals at frequencies f_i, f_j and f_k:

$$P_{ijk}\left(L\right) = \eta\left(\frac{d_{ijk}}{3}\frac{2\pi n^* L_{eff}}{\lambda S_{eff}}\right)^2 P_i(0)P_j(0)P_k(0)\exp\left(-\alpha L\right), \quad (10)$$

where η is the FWM efficiency, d_{ijk} is the degeneracy factor, $P_i(0)$, $P_j(0)$ and $P_k(0)$ are the powers of the input signals launched into a fiber. Parameter d_{ijk} depends on the number of channels affecting to FWM: $d_{ijk} = 3$ when $i = j$ and $d_{ijk} = 6$ when $i \neq j$. Using the formulae given in [6] and assuming that the launch power is limited to 4 mW, the following result is obtained: $\eta = 6.7 \times 10^{-6}$ (for NZ-DSF fiber implemented in the line) and $\eta = 3{,}4 \times 10^{-7}$ (for S-SMF fiber). The values obtained for signal-to-spurious FWM product ratios P_{out}/P_{ijk} (P_{out} is the output signal level) are shown in Table 1. It is evident that P_{out}/P_{ijk} exceed the value of 60 dB i.e. the minimum allowable for that system.

When analyzing the obtained results a conclusion can be made that for the system here considered the power penalty due to non-linear effects in the fiber can be considered negligible.

V. DETERMINING THE LENGTHS OF THE FIBER-OPTIC LINKS

When determining the maximum length of the optic line between headend and hub the limitations due to both the dispersion in the fiber and the minimum permissible level $P_{Rx\min}$ of the signal in the optic receiver input must be considered. The minimum level depends on the carrier-to-noise ratio at the receiver required to provide a bit error rate $BER \le 10^{-6}$. The following relation [7] can be used to compute CNR in the case signals are transmitted through *M*-multiple QAM:

$$BER \approx 2\left(1 - M^{-1}\right)\exp\left(-z\right)^2\left(z\sqrt{\pi}\right)^{-1}, \qquad (11)$$

where

$$z = \left[1.5 \cdot 10^{0.1\,CNR[\mathrm{dB}]} \big/ \left(M - 1\right)\right]^{0.5}. \qquad (12)$$

When $M = 256$ a *CNR* value of 33,4 dB will provide $BER = 10^{-6}$, which refers to the ideal optic channel.

With real optical channel there are power penalties (PP) that degrade the received signal to such an extent that error rates increase due to inter-symbol interference. Such an effect can be compensated by increasing the *CNR* required at the receiver. To calculate the new value of *CNR* the following equation can be used:

$$CNR^* = CNR + PP_D + PP_{ER} + PP_{PDL} + PP_{CT}, \qquad (13)$$

where PP_D, PP_{ER}, PP_{PDL}, PP_{CT} are the PP due to dispersion, non-ideal extinction ratio (ER) of the transmitter, polarization dependent loss (PDL) of same components in the network and crosstalk respectively. The PP components mentioned above are determined using the formulae in [8]. The total PP value in the optic line between headend and hub is PP = 12 dB, i.e. $CNR^* = 46$ dB.

The minimum received power providing the required *BER* (receiver sensitivity) can be determined as follows [7]:

$$P_{Rx\,\min} = CNR^* \cdot NF \cdot h \cdot f_c \cdot BR, \qquad (14)$$

where *NF* is the noise figure of EDFA, *h* is the Plank′s constant ($6.63 \cdot 10^{-34}$ J/Hz) and f_c is the optical carrier frequency (in the case $NF = 6$ dB and $f_c = 191{,}6$ THz). A value of $P_{Rx\,\min} = -10$ dBm will be obtained if the linear values of CNR^* and *NF* are introduced in (14).

TABLE 2
POWER BUDGET FOR THE OPTIC LINK BETWEEN HEDEND AND HUB

Elements	Loss, dB (L = 90 km)	Loss, dB (L = 60 km)
Laser Output	0	0
DWDM Multiplexer	–5.5	–5.5
NZ-DSF fiber	–19.8	–13.2
Splices	–4.5	–3.0
Connectors	–1.8	–1.8
DWDM Demultiplexer	–5.5	–5.5
Input into EDFA	–37.1	–29.0
Amplifier Output	–14.1	–6.0
Receiver Sensitivity	+10.0	+10.0
Margin	–4.1	+4.0

The power budget of the optic line must be computed in order to determine the maximum length of the optic line between headend and hub. Two cases are shown in Table 2. The first one refers to a line of $L = 90$ km and the second one - to $L = 60$ km. When determining the loss in the splices one should keep in mind that they are set up at every 2 km along the fiber each splice introducing a loss of 0.1 dB.

The results show that the maximum length of the optic line between headend and hub should not exceed 60 km in order to provide a minimum margin of 3 dB referring to the required receiver sensitivity. For the optic lines between hub and optic nodes the chosen type of S-SMF fiber has been used, which dispersion coefficient at 1310 nm is zero. Since those lines are usually twice as short there is no problem to provide the required minimum signal level at the receivers located in the optical nodes.

VI. CONCLUSION

The relations suggested in the paper make it possible for the maximum length of the optical line (with no amplification provided) and the admissible launch power to be determined when given the parameters of both the fiber chosen and the CATV system (such as bit rate, carrier-to-noise ratio, bit error rate, number of DWDM channels, channel spacing). The analysis reveals that owing to attenuation and dispersion in the chosen fibers the maximum length of the optical line between headend and hub is limited to 60 km. Besides, a fiber of the NZ-DSF type is to be used for the forward channel and a fiber of the S-SMF type is suitable for the reverse channel and the link between hub and optical nodes. It is proved that if the maximum launch power per channel is limited to 4 mW the worsening of the system parameters due to scattering effects and SPM, XPM and FWM effects in the fiber will be negligible.

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