УДК 681.7.068.4 **doi: 10.26906/SUNZ.2023.4.171**

Nikolai Starodubtsev, Sofia Khrustaleva, Victoria Nevlyudova, Rauf Allakhveranov

Kharkiv National University of Radio Electronics, Kharkiv, Ukraine

OPTIMISATION OF OPTICAL INFOCOMMUNICATION NETWORKS

Abstract. The article reviews existing approaches to network analysis, taking into account the topological properties of networks. A sequential analysis from a network link to the properties of a set of network links is carried out. The network link is analysed as a set of optical channels, and an analytical description of the transmission quality in such a channel is carried out. A model for calculating crosstalk in the paths of information and communication optical networks is proposed. As can be seen from the results, for an optical fibre of a given length, there is a number of steps for selecting the input polarisation ellipse for which the efficiency of the method is maximised. Also, with an increase in the number of steps, we observe a decrease in the efficiency of this compensation method. So, for an optical fibre of a given length at constant dynamics, there is a number of input signal polarisation ellipses for which the polarisation-mode dispersion will be minimal. For a particular fibre, this parameter (the number of input signals) must be selected, because this value is different for different fibres (within the range of 15-30 points).

Keywords: network, optical channel, model.

Introduction

Network analysis plays a crucial role in the design of optical information networks - it is thanks to the analytical apparatus that it becomes possible to draw a conclusion about the effectiveness of a particular network solution and identify mechanisms that can improve existing optical networks. In turn, a modern information and communication network is built using multi-channel optical paths, which are rather complex systems.

Therefore, there is a need to apply a consistent integration approach, starting with an analytical description of critical and important elements of the network structure and then summarising their properties in a global analytical description of the network.

Thus, it is necessary to form models of the links of the global network structure - tools for their study, considering the peculiarities of optical networks. It would also be useful to consider the approaches to analysing the link-network layer used in global backbone networks.

The analysis of an optical path link involves consideration of the entire set of influence parameters - both dispersion effects and nonlinear phenomena, noise and interference.

Consideration of existing approaches to network analysis is impossible without taking into account the topological properties of networks.

Analysis of the network path

The network path is an integral element of any network design. The main technical parameters of networks depend on the capacity of the network path.

Modern backbone networks have gradually replaced radio relay communication lines, copper symmetrical and coaxial cables as information channels due to a sharp increase in requirements for transmitted/received information.

It should be added that the requirements for the reliability of the transmitted information are increasing in proportion to the requirements for the volume of transmitted information.

Analysing the path capacity is an important technical task. In this article, we analyse paths with time and spectral compression of information, which are widely and actively used in backbone networks in most countries of the world and Ukraine.

In time compression, the dispersion properties of fibres impede high and ultra-high data transmission rates. The article discusses the main methods of dispersion control and proposes a method of its compensation.

To analyse the spectral compaction, a complex of nonlinear effects arising in the guiding system - optical fibre - is considered. A generalising mathematical model of the optical channel transmission quality of a group optical path of a *DWDM* system is derived.

The methodology for calculating the network structure congestion based on its topology, proposed in [1, 2], makes it possible to determine the level of interference in an optical system implemented using the technology of all-optical networks.

Topological analysis also made it possible to create a new toolkit - the flow structure - and manage it within the capabilities of high-level network management technologies.

Quality aspects of information transmission in *DWDM* systems

Q-factor is the *Electrical Signal-to-Noise Ratio (ESNR)* at the input of the receiver's decisive circuit. *ITU* Recommendation *O*.201 is intended to the measurement of Q-factor. The relationship between Q-factor and *BER* (bit error rate) is described in *ITU G. Sup.* 39.

According to *O*.201, the Q-factor is defined as:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 - \sigma_0},$$

where μ_1 and μ_0 - transmission voltage levels "1" and "0"; σ_1 and σ_0 - are deviations of the noise distribution at levels "1" and "0"; μ is the position of the decision threshold of the receiver logic circuit.

Q-factor is a system parameter that is determined by statistical patterns at the receiving end of the system when making decisions about the signal strength at any given time. To ensure that the quality of information transmission over a fibre optic transmission system channel is determined, these patterns must consider all the noise (and, consequently, interference) in the system.

Therefore, the Q-factor is one of the main parameters that characterises the optical channel of a transmission system, regardless of whether it is a spectrally compressed or single-channel system.

The main system parameter that characterises the quality characteristics of a system with a digital method of information transmission is the reliability of information transmission. The main system parameter that characterises the quality characteristics of a system with a digital method of information transmission is the reliability of information transmission. In digital transmission systems, the reliability of information transmission is characterised by the K_{er} error rate (BER) or the P_{er} error probability arising in the process of transmitting a certain number of messages (bits of information). In general, P_{er} can be interpreted as a function of the signal-to-noise ratio $\left(S/N\right)$, i.e.

$$P_{er} = f\left(S/N\right).$$

For binary digital communication channels, this function is the Crump function, which is tabulated and widely used in engineering calculations. Thus, the calculation of P_{er} is equivalent to the calculation of the signal-to-noise ratio, which, in turn, is determined by analysing the total system channel noise, which includes crosstalk, equipment noise, and fibre noise.

Accounting for nonlinear effects of optical components

Stimulated Raman Scattering (SRS) is a much lesser problem when compared to *Stimulated Brillouin Scattering (SBS)*. Real fibre-optic links (*FOCL*s) allow the use of an optical amplifier (*EDFA*) with a level of about 25 dBp or several amplifiers with a lower output level. *SRS* is similar in nature to *SBS* but is caused by different physical phenomena.

SRS is frequency-dependent and is more pronounced at short wavelengths than at long wavelengths (i.e., at higher frequencies). It can be noted that short-wave channels have a much lower amplitude compared to long-wave channels, i.e., there is a change in signal amplitudes for each channel. At the same time, it is the shorter-wave (high-frequency) channels that are subject to greater attenuation. In *WDM* systems, the effect of this type of scattering is to redistribute power from short-wave to long-wave channels. In this case, this phenomenon works like a Raman amplifier and the long-wave channels are amplified at the expense of the short-wave channels if the difference in wavelengths lies within the Raman gain band. This phenomenon can occur in quartz fibre, where gain can result from using a channel spacing of 200 nm.

Short-wave channels are the most impoverished, as their power can be simultaneously pumped into many channels at the same time. This redistribution of power between channels can be determined by the characteristics of the system because it depends on the nature of the bit arrangement - amplification occurs only when binary "1" are presented in both channels at the same time. Such amplification leads to an increase in power fluctuations, which increases the receiver's noise level and worsens its performance. Raman crosstalk can be avoided if the channel powers are so small that the gain is negligible along the entire length of the fibre. When Raman amplifiers are used in *DWDM* systems, it is necessary to consider the fact of crosstalk caused by the presence of several signals transmitted at different wavelengths.

SRS can occur in systems that use both single and multimode fibre. To observe *SRS* in the presence of only one channel, without the use of an optical amplifier, it is necessary to have a signal level of about +30 dBp. The literature [5,6] indicates that the threshold at which a 1 dB degradation is observed in a multichannel system caused by the presence of Raman radiation can be estimated from the inequality:

$$P_{tot} \cdot \Delta\lambda \cdot L_{eff} < 40\left[mW \cdot nm \cdot Mm\right], \qquad (1)$$

where P_{tot} – total capacity of all WDM channels (mW); $\Delta\lambda$ – the optical spectrum band (nm) in which these channels are distributed; L_{eff} – effective length, measured in megameters (Mm), which is defined as:

$$L_{eff} = \frac{4,343}{a}(1 - e^{-0.23aL}), \qquad (2)$$

where a - fibre attenuation coefficient (dB), L - fibre length (km).

According to (1), (2) we write from:

$$K_{SRS} = \frac{P_{tot} \cdot 4,343 \cdot \Delta\lambda}{40 \cdot a}\left(1 - e^{-0.23aL}\right)(\partial Bp). \qquad (3)$$

The *SRS* threshold for systems using G.653 fiber is slightly lower than for systems using G.652 fiber due to the smaller effective area of G.653 fiber. *SRS* has virtually no degradation in single-channel systems. The *SRS* effect actually limits the light output in the channel.

When using single-channel systems, unwanted spectrum regions can be eliminated by using filters. For *WDM* systems, there are currently practically no techniques that would allow to eliminate the *SRS* effect. However, the impact of *SRS* can be decreased by reducing the input optical power.

SBS (Stimulated Brillouin Scattering) sets an upper limit on the level of optical power that can be transmitted by an optical fibre. When a certain level of optical power, called the *SBS* threshold, is exceeded, an acoustic wave is generated in the OF, which changes the refractive index *n*. Changes in *n* cause light scattering, which leads to additional generation of acoustic waves. To excite the Mandelstam-Brillouin scattering, the spectral density of the initial radiation should be much higher than for Raman scattering - 10 mW in the frequency band 10-50 MHz. As a result of this effect, a wave with a shifted frequency (*Stokes wave*) propagates in the opposite direction to the light source, which reduces the useful transmitted optical power. This limits the maximum achievable power that can be transmitted by the transmitter into the line. For example, at a wavelength of

1550 nm, the scattered light is shifted to the right by approximately 11 GHz. This scattering *(SBS)* has the lowest threshold power. It has been shown that the *SBS* threshold can vary depending on the type of fibre and even depending on the specific fibre. The threshold is on the order of 5 to 10 mW for narrowband externally modulated lasers. For directly modulated lasers, this power can be around 20-30 mW. For G.653 fibres, the *SBS* threshold is slightly lower than for G.652 systems. This is due to the smaller effective area of G.653 fibres. It can also be said that this is true for all the nonlinear effects considered. The *SBS* threshold is sensitive to the spectral width of the radiation source and the radiated power level. However, it does not depend on the number of *WDM* channels.

In addition to the effect of reducing the useful power, noise occurs (the relative noise intensity *(RIN)* increases, for example, from -155 dB/Hz to -138 dB/Hz), which worsens the BER (probability of error) characteristics. It is especially important to control *SBS* in high-speed transport optical systems, necessarily using external modulators and *CW (Continuous Wave)* laser sources.

The resulting acoustic wave is hypersonic in nature, and its frequency spectrum can be located in the band up to 10...13 THz (10^{13} Hz). *SBS* limits the level of light energy that can be transmitted by the fibre. The level of input power introduced into the fibre, at which a sharp increase occurs, is defined as the *SBS* threshold, and is described by the formula:

$$P_{th} = 21 \cdot \frac{KA_{eff}}{gL_{eff}} \cdot \frac{\Delta\upsilon_p - \Delta\upsilon_B}{\Delta\upsilon_B}, \qquad (4)$$

where g – Brillouin gain coefficient, A_{eff} – effective core area, K is a constant determined by the degree of polarisation state freedom, for G.652 – $K = 2$.

$\Delta\upsilon_B$ і$\Delta\upsilon_P$ are variables representing the spectral width of the Brillouin band and the pumping source, respectively; L_{eff} – effective length.

The degradation caused by *SBS* does not occur in systems where the line width of the radiation source is significantly greater than the Brillouin bandwidth or where the signal power is less than the *SBS* threshold power.

It can be assumed [5] that if the theoretical threshold (4) is exceeded, the *KSBS* degradation will be approximately 10 dBp per channel, which is absolutely unacceptable.

Four-wave mixing (FWM) occurs if two signals with different frequencies and sufficiently high intensity are introduced into the channel - the spectrum of the scattered signal will contain components with four frequencies (taking into account Rayleigh-Mandelstam scattering), and in the case of superposition of two of the frequencies on each other, which is quite possible, photons with frequencies that differ from the carrier appear

$$v_{c3} = v_u - 2\omega_c .$$

The frequency spectrum of the scattered radiation is expanded, and some of the components can be enhanced by suppressing others. Given N optical carriers, the number of components resulting from the FWM is determined by the ratio (5):

$$0,5N^2(N-1) . \qquad (5)$$

The FWM can also occur with a single optical signal that transmits information by amplitude modulation, i.e., its spectrum consists of three main components: the central frequency and side frequencies; at high transmission rates, the side frequencies are very far apart from the central frequency, so each of them is an independent carrier from the point of view of the FWM. The effect of FWM on transmission is manifested as additional crosstalk, inter-symbol interference at high transmission rates, and impoverishment of the power of signals from some channels due to the influence of signals from other channels.

The effectiveness of the FFS is also sensitive to the total optical power in the fibre. An approximate formula for calculating the *FWMP* efficiency for SMF-28, taking into account the frequency spacing of N channels d_f can be written as:

$$FWM\left[\partial B\right] \approx -57 + 10\lg\left(\frac{N}{d_f}\right) + \frac{1200}{d_f}, \qquad (6)$$

Thus, for an 8-channel *CWDM* with a frequency spacing of df = 200 GHz (192.4 - 193.8 THz), the *FWMP* will be ~ -46.7 dB, and for a 16-channel *CWDM* with a frequency spacing of 100 GHz, the *FWMP* will be ~ 37.7 dB.

Recall that the electrical equivalent of *FWMP* is equal to twice the optical efficiency of *FWMP* and for the latter case will be equal to -75.4 dB.

FWM has the greatest parasitic effect in FOCs in which the optical path is built on G.653 *DSF* zero-dispersion shifted fibre; FWM is practically not manifested in single-mode standard G.652 *SMF* fibre. Experiments have shown that for G.653 fibres, this interference is unacceptable (up to 20 dBp), while for G.652 it is practically absent.

In order to adequately suppress the generation of FWM products, the industry has proposed the use of fibres with a minimum permissible but non-zero dispersion in the gain region of optical amplifiers. As an alternative, it is proposed to use alternating spans with opposite dispersions. Of course, it is possible to provide an increase in the channel spacing and the existence of an uneven spacing between them, thereby reducing the level of interference from the FWM.

Active components of optical systems with spectral channel compression

If certain DWDM specifications require compliance with a small emission bandwidth (0.01...0.5 nm) G.692, G.957, not all emitters provide it.

The spectrum of the intensity-modulated signal resembles that of an AM signal. It contains lateral components, and the spectrum of the output signal must be limited to the first harmonic of the signal clock. Frequency instability for STM-64 at 10 GHz will cause overlap with the frequencies of the neighbouring group channel, unacceptable noise growth, signal suppression and system malfunction. For STM-256, even half the tolerances of the STM-64 system are out of the question. That is, the frequency stabilisation system must be of very high quality. For STM-64, the width of the spectral line should not exceed 0.08 nm at spectral intervals of 50 GHz. For STM-16 = ±0.5 nm (G.957).

Exit from the specified frequency bands leads to the appearance of unacceptable crosstalk. In principle, the issue can be solved by introducing additional filters, but this will entail a significant increase in the cost of the system and the need to use additional amplifiers.

Let us calculate the noise figure of the radiation source together with the photodetector using the analysis formulas from [6-7]:

$$K_{N.RS} + K_{N.FD} = \frac{m^2}{2\Delta\nu_{chan}}\left(R + \frac{2q}{P_{in}S} + \frac{I_n^2}{P_{in}^2 S^2}\right)^{-1}, \quad (7)$$

where m - channel optical modulation index, often referred to as *OMI (Optical Modulation Index)*.

It is usually expressed as a percentage, but a dimensionless value, such as $m_{[\%]}/100$, should be substituted into the calculation formulas.

For example, m = 4% is equivalent to m = 0.04; $\Delta\upsilon_{chan}$– channel noise band in a selected band; R – relative intensity of noise *RIN (Relative Intensity Noise)*, which is calculated as the noise power reduced to a 1 Hz band relative to the optical power of the unmodulated carrier, dB/Hz; q – electron charge; S – sensitivity of the optical module, which depends on the optical wavelength.

Typical values of S are S_{1310} = 0.85 A/W and S_{1550} = 0.95 A/W for wavelengths of 1310 nm and 1550 nm, respectively. Physically, the S parameter indicates the current (in mA) that will appear at the output of the photodetector when an optical power of 1 mW (0 dBp) is applied to its input;

I_n is the equivalent noise thermal current of the amplifier, measured in pA/Hz. A typical value of I_n for a transimpedance stage based on a *GaAs* field-effect transistor is 7...8 $nA/\sqrt{Hz}$. Nowadays, amplifying transistors with low noise and very high input impedance have appeared, and they have an input noise current of up to 5 $nA/\sqrt{Hz}$.

In addition, as the frequency band is limited, the total useful power will decrease, and as it grows beyond the limit, it will decrease due to redistribution to the prohibited out-of-channel frequency range, thus initiating a decrease in the signal-to-noise ratio, which, in turn, is equivalent to a deterioration in the quality of information transmission in the system.

Let us write down the interchannel interference level coefficient of an optical signal, which characterises power losses [5-6]:

$$K_{chan} = P_{chan} \cdot e^{-5\frac{\Delta\upsilon_{bands}}{\Delta\upsilon_{in}}}, \quad (8)$$

where P_{chan} – optical channel power; $\Delta\upsilon_{bands}$ – frequency range allocated to a channel.

The optical amplifier increases the level of not only the useful optical signal, but also the parasitic harmonics, which, in fact, form the basis for crosstalk in optical systems. In addition, optical amplifiers (both *EDFA* and *SRS*) have their own noise.

The noise figure (*NF*) of an amplifier is caused by amplified spontaneous emission (*ASE*). The *ASE* noise figure is determined from the following expression [5]:

$$NF = \frac{2P_{ASE}}{h\nu_c\Delta\nu\left(G_A - 1\right)}(\partial B), \quad (9)$$

where P_{ASE} - power of amplified spontaneous radiation; h - Planck's constant; ν_c - signal frequency.

$$P_{ASE} = 2n_s h\nu\Delta\nu_A(G_A - 1), \quad (10)$$

where n_s - spontaneous emission rate.

The spontaneous emission factor can take on a value from 1 to 10 for optical amplifiers with G_A >1. For typical erbium amplifiers of modern fibre-optic information transmission systems with G_A >10 dB, the typical NF value is in the range of 3dB < NF < 6dB. If the amplifiers are switched on in successive stages, it can be shown that the noise figure of the first stage determines the noise figure of the entire amplifier. The noise figure NF_R of a Raman distributed amplifier is determined from the expression:

$$NF_R = 2/\ln G_R, \quad (11)$$

where G_R - is the coefficient of gain of the Raman amplifier, which is determined from the expression:

$$G_R = e^{\frac{g_R P_h L}{A_{ef}}}, \quad (12)$$

where g_R – Raman coefficient; P_h – pumping power; A_{ef} – effective cross-sectional area; L – fibre length.

We can assume g_R = 7· 10^{-17} km/W. The actual pumping power ranges from 0.5...0.8 W to several watts [6]. Thus, we obtain the total noise figure of the optical amplifier:

$$K_{N.OA} = \frac{1}{M}\sum_{M} K_{N.chan} \cdot \left(NF_{A_M} - K_{A_M}\right),, \quad (13)$$

where NF_A - noise of a particular amplifier; K_A - coefficient of gain of the amplifier; $K_{N.chan}$ - noise figure of the transmission channel obtained before each optical amplifier; M - number of amplifiers.

The photodetector noise and, accordingly, the coefficient $K_{N.chan}$ are set based on the information provided by the manufacturers.

$K_{N.chan}$ is also calculated based on the data provided by the equipment manufacturers.

In practice, a 3 dB margin is taken into account in terms of signal-to-noise ratio due to the frequency-exchange coding (*FEC)* used in backbone fibre-optic transmission systems. This margin is introduced as an improvement of the signal-to-noise ratio at the photodetector and is not the maximum possible.

Conclusions

In this article, we have considered a sequential analysis from the network link to the properties of a set of network links.

The network link is analysed as a set of optical channels, and an analytical description of the transmission quality in such a channel is given.

A model for calculating crosstalk in optical network paths is proposed.

As can be seen from the results, for an optical fibre of a given length, there is a number of steps for selecting the input polarisation ellipse for which the efficiency of the method is maximised.

Also, with an increase in the number of steps, we observe a decrease in the efficiency of this compensation method. This is due to the fact that during the selection of the minimum value, transmission is also carried out, and the value of the differential group delay is not minimal. Of course, with a decrease in dynamics (an increase in the time during which the optical fibre does not change), the efficiency of using the compensation method increases.

So, for an optical fibre of a given length at constant dynamics, there is a number of input signal polarisation ellipses for which the polarisation-mode dispersion will be minimal.

For a particular fibre, this parameter (the number of input signals) must be selected, because this value is different for different fibres (within the range of 15-30 points).

The speed of determining one value of differential group delay at the output of the optical line path and transferring this value to the transmitting side is fixed, and therefore 20 measurements and 100 measurements (for different numbers of input channels) also take this time.

References

1. Korets M.S. Materials science of information technology: a textbook / M.S. Korets, I.G. Tregub, S.M. Yashanov; Ministry of Education and Science, Youth and Sports of Ukraine, National Pedagogical Dragomanov University. - K.: Drahomanov National Pedagogical University, 2011. - 589 p.
2. Ivanenko I. M. Structural materials in the production of inorganic substances / Textbook for students of speciality 161 "Chemical Technology and Engineering" / I. M. Ivanenko - Kyiv: Igor Sikorsky Kyiv Polytechnic Institute, 2018. - 242 p.
3. Physicochemistry and technology of organic and inorganic carbon fibres: Monograph / Edited by Sirenko H.O. and Komashko O.V. - Ivano-Frankivsk: V.P. Suprun Publishing House, 2019. Suprun V.P., 2019. - 170 p.
4. Glass, ferroelectrics, graphene, high-temperature superconductors. - Part 6: a textbook / O.T. Bogorosh, S.O. Voronov, R.I. Petryshyn, V.M. Kramar, O.G. Shayko-Shaykovsky (eds.). Chernivtsi: Yuriy Fedkovych Chernivtsi National University. 2022. - 312 p.
5. Panasiuk B.C., Savruk M.P., Datsyshyn O.P. Stress distribution near cracks in plates and shells. - Kyiv: Naukova Dumka, 1976. - 443 p.

Received (Надійшла) 2.10.2023
Accepted for publication (Прийнята до друку) 06.12.2023

Оптимізація оптичних інфокомунікаційних мереж

М. Г. Стародубцев, С. В. Хрустальова, В. В. Невлюдова, Р. Ю. Аллахверанов

Анотація. У статті розглянуто наявні підходи до мережевого аналізу, з урахуванням топологічних властивостей мереж. Проведено послідовний аналіз від мережевої ланки до властивостей сукупності мережевих ланок. Проаналізовано мережеву ланку як сукупність оптичних каналів, проведено аналітичний опис якості передачі в такому каналі. Запропоновано модель для розрахунку перехресних завад у трактах інфокомунікаційних оптичних мереж. Як видно з отриманих результатів, для оптичного волокна заданої довжини існує така кількість кроків вибору вхідного еліпса поляризації, для якої ефективність методу є максимальною. Також при збільшенні кількості кроків ми спостерігаємо падіння ефективності використання такого методу компенсації. Отже, для ОВ заданої довжини за постійної динаміки існує така кількість еліпсів поляризації вхідного сигналу, для якої поляризаційно-модова дисперсія буде мінімальною. Для конкретного волокна цей параметр (кількість вхідних сигналів) потрібно добирати, бо для різних волокон це значення є різним (перебуває в межах 15-30 точок).

Ключові слова: мережа, оптичний канал, модель.