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Energy efficiency of codes under the nonlinear effects in optical communication channels

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ABSTRACT: The paper reviewed the main issues of error correction in optical fiber distortions based on nonlinear effects. At the same time, evaluated mechanisms for energy efficiency of codes with parameters that affect the quality of its transmission, also developed the results of experiments on the application of codes. In addition, calculated error statistics on data transmission channels.

KEY WORDS: optical channel,nonlinear effect, codes, fiber optic communication, pattern effect, triplet, signal to noise ratio, modulation, error frequency, codes efficiency.

I. INTRODUCTION

Today, fiber light conductors are considered as the optimal data transmission medium. To date, the fact that such transmission environment has increased to 100 Tbit/s clearly demonstrates its physical and technical capabilities [1].In order to achieve such transmission speeds, manufacturers use WDM (Wavelength Division Multiplexing) technology, which allows data to be transmitted over multiple frequency channels simultaneously. In addition, the use of other modulation formats with high spectral efficiency (e.g., quadratic-amplitude modulation) [2] formats is being more actively applied.

However, when the optical signal is division by frequency, it begins to be significantly affected by the characteristics of the data transmission medium in the spectral field. The most important of these are nonlinear effects. While in the early termsof the development of fiber optic transmission systems there were problems due to extinction and dispersion, nowadays the problems related to nonlinear effects in high-speed digital data transmission in DWDM systems are in the first place.

II. STATEMENT OF THE PROBLEM

An increase in channel power, an increase in the number of channels, and the decrease in pitch between channels that occur in the optical fiber depend on nonlinearities characteristics system. Due to nonlinearities, the number of combination harmonics and interference increases, which results in a decrease of the optical signal / noise ratio (OSNR), as well as the decrease in the quality of optical channels and noise protection. As a result, it will not be possible to transmit signals with the required quality.

Recent research on the distortion of optical signals allows us to determine their effect, both quantitatively and qualitatively. Quantitative studies have been conducted to determine the statistics of data transmission errors using amplitude [3, 4] and phase [5, 6] modulation formats. From a qualitative point of view, the analysis of the received position points in the spatial plane and the energy distribution of received symbols were carried out[7].

In experiments conducted at the power level of the initial signal (10 mW), it was observed that the number of errors strongly depends on the type of data transmitted (pattern effect). For a five-channel system with a phase binary format by phase difference [5], error statistics on binary triplets were observed (Fig. 1).

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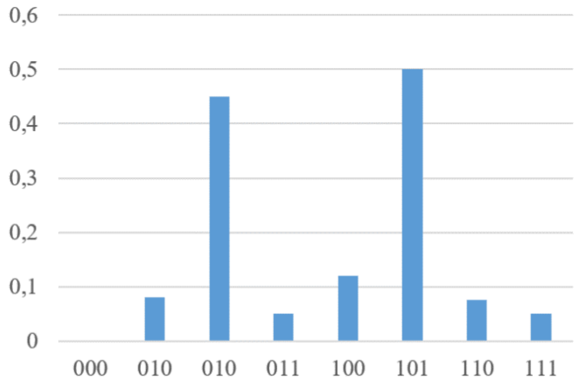

Figure 1. Histogram of error statistics on binary triplets

In this numerical experiment, only 5 million bits were transmitted and 125,258 errors were obtained, i.e., the error rate was $2.5 \cdot 10^{-2}$. It can be seen that 85% of these errors occurred in the central bits of triplets 010 and 101.The magnitude of the errors in the output of system was such that the FEC (Forward Error Correction) tools do not provide optimal decoding quality, and the tools that can provide (for example, turbocodes) are not used in fiber-optic communication lines due to their complexity.In this regard, there is a problem of ensuring high quality data transmission in such conditions. In this case, the exact problem is solved by using special codes that reduce the number of errors in the received data sequence.

III. SOLUTIONS

It is known that in analog communication the signal/noise ratio, expressed in decibels (dB), is used as a criterion for the quality of channel – the ratio of the average signal strength to the average noise power. In digital communication, this criterion is replaced by a standardized version of the E_b/N_0value - signal / noise ratio. Where Eb is the energy of the bit, N_0 is the spectral density of the noise power, defined as the ratio of the noise power to the width of the transmission band.

Based on this characteristic of the channel, it can be seen that the probability of occurrence of symbol errors in the information bits in the network depends on the E_b/N_0ratio. The curve showing this relationship will usually have aform shown in Figure 2. This figure shows the correlations for phase modulation formats – BPSK (Binary phase-shift after) coherent acceptance and DBPSA (Differential binary phase-shift after) noncoherent format. For the basic modulation formats of the signal, there are analytical expressions of the dependence of the value on the E_b/N_0 ratio.

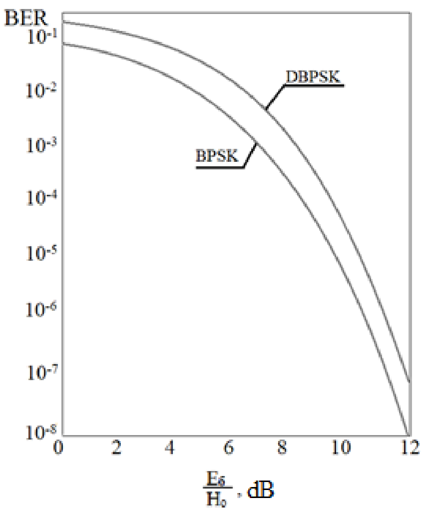

Figure 2. The frequency of errors depends on the noise level curves in phase modulation formats

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Fig. 3 shows the relative performance of data transmission over an optical channel encoded with different interference codes. The figure shows the Q-factor values along the abscissa axis, which is a measure of the optical communication system quality and is directly related to the SNR ratio for the channel.

In evaluating the effectiveness of restricted codes, it is important that they have a positive effect on the practical application of the codes (both limited and error-correcting). It allows you to get the frequency of small errors in data without physicall altering the data transmission across the channel.

From Fig. 3 it can be seen that when using the RS (255,239) Reed-Solomon code, it is possible to reduce the frequency of errors in the channel from 10^{-3} to 10^{-9}. If the Reed-Solomon code is replaced by the LDPC (Low-density parity-check code), then an error value of 10^{-9} is achieved at a frequency of input errors equal to 10^{-2}.When using codes, the reserve of the channel is increased by maintaining the signal quality in the event of deterioration of the characteristics relative to the initial values. This can be achieved at a smaller E_b/N_0 ratio than the value required to transmit data when the error value is not coded.

The efficiency of the code is usually determined by how much the E_b/N_0 SNR ratio can be reduced for the coded signal provided that the error frequency is kept constant. Such efficiency is typically measured in dB, indicating from an engineering point of view that the E_b/N_0 ratio (i.e., the quality of the physical signal) within that range indicates a possible decrease in the actual quality of data reception.

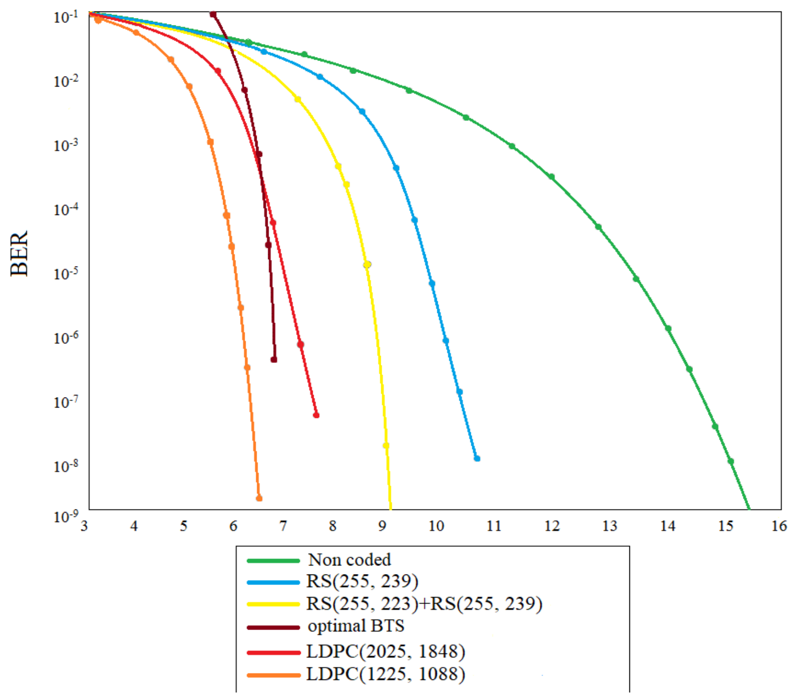

Figure 3. Characteristics of the frequency of errors for different interference codes depending on the quality of data transmission

While evaluating the codes constructed above in terms of their effectiveness, its comparative characteristics are of particular importance. Typically, the effectiveness of any interference code is evaluated in the channel only under conditions that are affected by additive white Gaussian noise (AWGN) (Figure 3).

However, due to some peculiarities of the investigated object - optical fiber channels, precisely the presence of nonlinear effects in them, the evaluation of codes effectiveness using AWGN does not give clear results, because the nature of nonlinearities effect is different from Gaussian noise. In such circumstances, the question of finding a way to evaluate the effectiveness of interfering codes in conditions affected by nonlinear changes in the channel remains relevant. This issue is still actual today, when increasing the transmittance of optical channels is of great importance, as the presence of interference depending on the signal type and its strength does not allow using certain evaluation methods.

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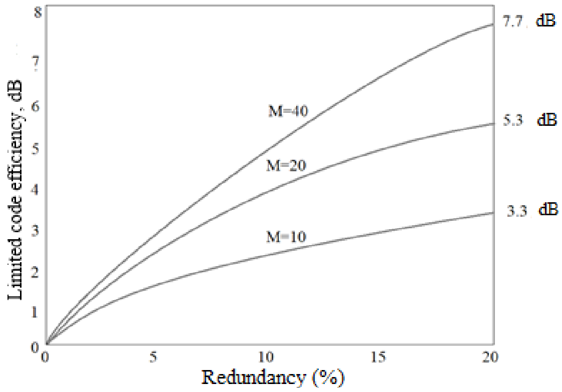

Figure 4. 101 The effectiveness of a limited code that loses a triplet depends on its redundancy

We will analyze the effect that comes from the code that loses 101 triplets from the message. Hence, the error vector $Q=q\cdot(1,1,1,1,1,M,1,1)$, where q and M are optional positive numbers and $q\cdot M<0,5$, otherwise in decoding, the center bit of the triplet can be replaced with the opposite bit $1-q\cdot M<0,5$ in the probability of error. In this case, the frequency of occurrence of the BER error in the transmitted data is$BER=\sum_{k=0}^{7} Q_k P_k$, where the probability of occurrence of the triplet P_k – k.

If 101 triplets are transmitted in a low quality on the channel, then this characteristic is negative, because the ratio of the initial BER value to the value of the encoded signal is not less than one, the efficiency of the code to different values of asymmetry parameter, as well as 101 triplet transmission errors a graph is given that characterizes the dependence on the level (M value) (Figure 4).

Such an approach will undoubtedly provide an understanding of the appropriateness of coding use, but it has its shortcomings. Moreover, it does not consider such an important aspect as the spread of errors on the coded word when there is only one error in the adoption of the use of limited code in practice.

For data not encoded with $BER_0$and$BLER_0$, we define it with $BER$and$BLER$ values. We also set the appropriate values for the data encoded with $BER(\varepsilon)$ ва $BLER(\varepsilon)$. It is not difficult to see that when the error vector is equal to $Q=q\cdot(1,1,1,1,1,M,1,1)$, andwhen $BER_0=q+\frac{1}{8}q(M-1)$, it equals to $BER(\varepsilon)=q+P_5(\varepsilon)q(M-1)$. In this case, the value of the block error is $BLER_0=1-(1-BER_0)^p$, where p is the size of the initial data block (the data block used in coding, the coded data block is $p+R(p, \varepsilon)$, where $R(p, \varepsilon)$- code redundancy).

This block code has some kind of redundancy $R(p, \varepsilon)$, it depends on the length of the block and the value of e, in which case the frequency of errors in the data block is easy to calculate by the following formula:

$$BLER(\varepsilon)=1-(1-BER(\varepsilon))^{p(1+R(p,\varepsilon))} \quad (1)$$

Using this ratio, the value $BER'(\varepsilon)=1-(1-BLER(\varepsilon))^{1/p}$can be found. The error frequency of $BER'(\varepsilon)$corresponds to the frequency of $p$bit errors that a block of encoded data has, where the frequency of block errors is equal to $BER'(\varepsilon)$. After the elements are changed, the relationship between $BER'(\varepsilon)$ and $BER(\varepsilon)$can be reached:

$$BER'(\varepsilon)=1-(1-BER(\varepsilon))^{1+R(p,\varepsilon)} \quad (2)$$

For the desired $R(p, \varepsilon)$ redundancy value is $BER'(\varepsilon)>BER(\varepsilon)$. In contrast to the direct comparison of the BER value before coding with the BER value after coding, the correlation found is that the coded data will have a larger size than the original data.

We now define the code efficiency parameter as follows. We determine the parameters of the AWGN noise that fits to the frequency of bit errors detected above. The following noise that affects is called equivalent noise. Let A (M, q) be the standard deviation of the affected noise, then we determine the efficiency of the code as follows:

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$$D = 20\log_{10}\frac{A(M,q)}{A_c(M,q,\varepsilon)} \quad (3)$$

here:
$A_c(M, q, \varepsilon)$ – the value of the affected noise after coding;
$A(M, q)$ – indicates the standard deviation of the noise value acting before coding.

If $A^2(M,q)=\sigma^2$, $A_c^2(M, q, \varepsilon)= \sigma'^2$ designation is accepted, thenthe connection between σ and BER is given by the following ratio:

$$BER_0 = \frac{1}{2}F\left(\frac{1}{\sigma\sqrt{2}}\right), BER'(\varepsilon) = \frac{1}{2}F\left(\frac{1}{\sigma'\sqrt{2}}\right) \quad (4)$$

here:
$F(x)=\frac{2}{\sqrt{\pi}}\int_x^\infty e^{-t^2}dt$ – additional error function.
Based on the given data, it is possible to construct a code efficiency graph for different M values (Figure 5).

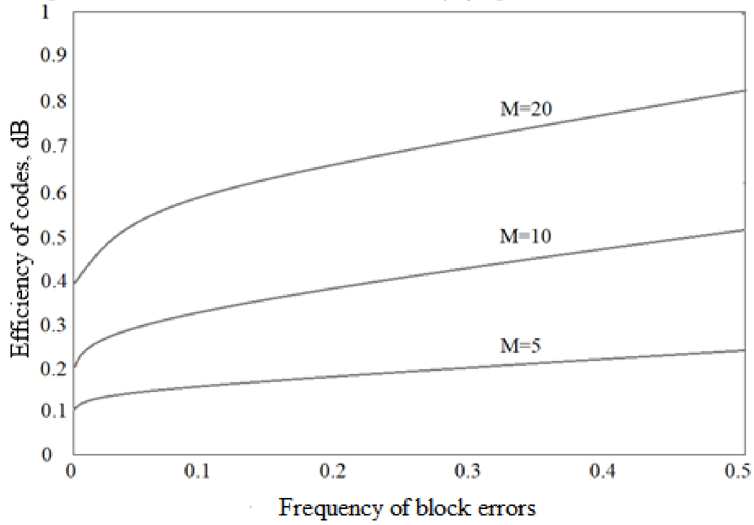

Figure 5. The efficiency of a block code that loses 101 triplets

When m=10, the efficiency of the code ranges from 0.3 dB to 0.5 dB, depending on the initial q value, where q is the probability of errors in any triplet except the triplet *q-101*. Efficiency in the order of 0.5 dB can be for a channel with a frequency of BLER = 0.3 block errors, which corresponds to a value of $BER=2.7\cdot 10^{-3}$, this condition is applicable to many applications.

Table 1. Error statistics on data transmission channels

Triplet	**Channel 1**	**Channel 2**	**Channel 3**	**Channel 4**	**Channel 5**
000	0	2	4	2	6
001	1216	1353	1471	1559	1604
010	**7081**	**7154**	**7783**	**8299**	**8470**
011	111	123	181	190	192
100	1064	1250	1286	1422	1464
101	**7650**	**8029**	**8590**	**9298**	**9354**
110	94	122	134	145	168
111	42	53	70	60	93

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Depending on the type of channel error statistics according to the adaptive code description, it can be seen that the error statistics obtained in modeling its optical fiber communication line (Table 1) are developed without tripping the error characteristics of triplets on different channels.

The experimental curves in which errors frequency depends on the level of noise in the channel can be obtained for each interfering code. It is based on the redundancy of codes as well as the comparison of different coding schemes with each other.

IV. CONCLUSIONS

There are several reasons why using codes in modern communication channels is so important. They enables you to get the frequency of small errors in data without physicall altering the data transmission across the channel.When using codes, the reserve of the channel is increased by maintaining the signal quality in the event of deterioration of the characteristics relative to the initial values. This can be achieved at a smaller E_b/N_0ratio than the value required to transmit data when the error value is not coded.

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