The Simulation Model of Optical Transport System and Its Applications to Efficient Error Control Techniques Design

Predrag Ivaniš and Dušan Drajić

***Abstract*—Modeling of the all effects that appear during the transmission of optical signal represents the basic condition for performance evaluation of the optical communication system. The new generation optical transport networks are based on the wavelength division multiplexing (WDM). In this paper, the simulation model that includes a typical effects that appear in the every channel of WDM system, when data rate in each of then is not greater than 10 Gb/s. Using the simulation model, the capacity of the channel is numerically evaluated, and the spectral efficiency of the techniques that combine multilevel modulation and error control coding is compared with this theoretical limits.**

***Index Terms*—Channel capacity, channel modeling, error control coding, multilevel modulation, optical transport system, wavelength multiplex division.**

I. INTRODUCTION

It is well-known that the error control coding represents an efficient technique that enables the reliable data transmission under difficult conditions in transmittion channel. Furthermore, combining the error control codes with multilevel modulations (e.g. trellis coding modulation), the error rate can be reduced without decreasing the data rate or increasing spectrum bandwidth [1].

Although the error control techniques are successfully applied in digital communication systems for decades, it is almost neglected in optical system design for a long time. Reliable transmission is provided by applying a sufficient number of amplifiers and increase of the data rate is provided by increasing the bandwidth, the resource that seemed to be almost inexhaustible in optical fiber.

However, it has been shown recently that reliability of data transmission in optical transport systems can be extensively increased using the forward error correction (FEC). It is especially significant when throughput in every particular channel is heavy and when long-haul transmission has to be performed using optical fiber channels [2].

In such a system, it is usually considered that the data rates are at least 10 Gb/s per one channel of Wavelength Division Multiplexing (WDM) optical system, and distances between amplifiers are greater than 40km, when the transmission is usually performed in spectral window about 1,55 μm. This window is about 25 THz wide (1450nm-1650nm) [3], but the greater demands for high speed communication and some actual services (video signal transmission, HDTV, high speed Internet access) require additional increase of data rates. It can be performed using several approaches [4]:

a. *Increase of the optical bandwidth of every particular channel.* Beside the bandwidth of optical fiber itself, this quantity is determined with range of frequencies where the amplifiers transfer functions are linear, and it cannot be increased infinitely.

b. *Increase of the channel number*, i.e., number of the different wavelengths in WDM multiplex. In such a case, the every channel bandwidth is previously limited, and throughput in every particular channel is determined by speed of used electronic components. In every wavelength, the separate set of amplifiers and the other equipment is used. Number of the channels in WDM system is limited according to optical fiber bandwidth and system complexity.

c. *Increase of the spectral efficiency*, e.g. the throughput that can be achieved in every separate WDM channel for the fixed bandwidth. This quantity is theoretically determined by the channel capacity (fundamental quantity in Information theory, defined by Shannon in his famous paper [5]), and practically determined by using the modulation type and error correction code, applied in the considered communication system.

During the previous development of the transport optical systems, increase of the information data rate is performed by increasing the bandwidth or adding of the new channels in WDM multiplex system. In this moment, it appears that information data rate cannot be sufficiently increased using these methods, so techniques that inherently provide high spectral efficiency became more important. Two basic techniques of this type are multilevel modulations and error correction codes (ECC) [1,3].

In the next section, two the most common solutions for

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transmission of packet traffic through optical transport network are presented. In newer standard, the obligatory protection of transmitted information using the linear block code is proposed. In such a system, Rid Solomon code (255,239) is chosen to reduce the error rate in transmission and increase the length between the regenerators (very important in undersea optical transport systems). This fact motivated the researchers to consider the combination of multilevel modulation and error control codes that leads to the increased spectral efficiency. In this paper, we describe a simulation model and apply it to estimate capacity of the corresponding optical system. Furthermore, we will determine performances (bit error rate and spectral efficiency) of some error correction codes, previously proposed in the literature.

II. OVERVIEW OF THE OPTICAL TRANSPORT NETWORK TECHNOLOGY

Synchronous digital hierarchy (SDH) today represents an dominant technology that provide reliable and wide-spread transmission of digital signals over optical fiber channels. Multiplexing protocol in synchronous optical networks (SONET - *Synchronous Optical Networking*) is designed to support transmission of Time Division Multiplex (TDM) traffic. These networks are connection-oriented, and its synchronous nature requires fixed frame size and constant data rate [6]. Typical throughputs in SDH/SONET network are presented in Table I. The STM-0 frame structure is consisted of 90 columns and 9 rows, where basic cell of the frame is one octet, as it is presented in Fig. 1. STM frames with greater data rates have more columns (variable size of the frame) but its duration is always 125µs.

TABLE I
SDH/SONET THROUGHPUTS

SONET	SDH	Throughput (Mb/s)
OC-1	STM-0	51.84
OC-3	STM-1	155.52
OC-12	STM-4	622.08
OC-48	STM-16	2488.32
OC-192	STM-64	9953.28
OC-768	STM-256	39813.12

Is expected that the Ethernet will be the serious competitor to the other technologies applied in the transport networks, and combination of Ethernet and SDH seems to be the most economic solution for design of the regional communications networks (WAN – *Wide Area Network*). However, as most of the Ethernet packets have variable size, the SDH based transport networks are not the most suitable for its transmission. Furthermore, the networks based on Ethernet technology are connectionless oriented and number of packets transmitted in the time unit is not fixed in these networks.

In the previous period, the several practical solutions for optimization of the Ethernet packet transmission over SDH networks appear. One of them is known as OTS 166/622 IRITEL transport system, where GFP (*Generic Framing Procedure*), VCAT (*Virtual Concatenation*) and LCAS (*Link Capacity Adjustment Scheme*) mechanisms are implemented. This techniques makes possible efficient encapsulation of Ethernet packets in SDH frames, segmentation into the smaller pieces (containers) and dynamical allocation of available channel capacity inside the SDH "transport path" [7]. The more sophisticated solution, that support transmission of six independent STM-16 (2.5Gb/s) optical interfaces for distances up to 100km, based on WDM technology, is recently described in [8].

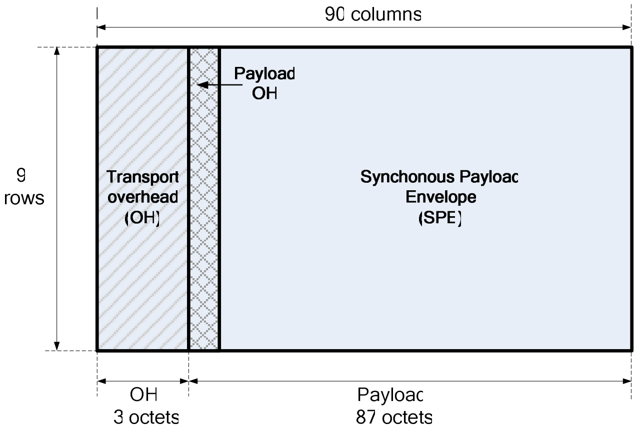

Fig. 1. The STM-0 frame structure.

In a few previous years, a lot of effort is made to develop the interface that could support transmission of packet traffic of various nature (SDH/SONET frames, ATM, IP, Ethernet packets) over the optical transport network (OTN). The standard is accepted as IEEE recommendation G709 [9], and it is also known as Optical Transport Hierarchy (OTH) standard, that basically has to support transmission of the different services over WDM optical system.

As an example of the frame structure in OTH system, in the following sentences the structure of OTU-2 frame, with the throughput of approximately 10Gb/s (practically the same as in 10Gb-Ethernet networks) will be explained. The frame is consisted of one header octet, followed by the transmitted data (*payload*), with length of k-1=238 octets, obtaining the information word that enter the Reed Solomon code RS(255,239). This way, the subframes with length of n=255 octets are generated (one codeword corresponds to one subframe). Using the concatenation of six successive subframes, as it is shown in Fig. 2, one row of frame is generated. As it is shown in Fig. 3, one OTU frame is consisted of the four rows with length of 4090 octets.

The overview of the remaining hierarchy levels and its comparation with SDH hierarchy are given in Table II. Although the information data rate (throughput of data located in *payload* part) is identical as the line date rate in SDH/SONET network, line data rate in the corresponding OTH network is multiplied by factor 255/239, since the Reed-Solomon code (255,239) is applied. This enable the simple conversion of SDH frames into the OTU frames. For the case of OTU-2 frames, the similar operation can be performed for

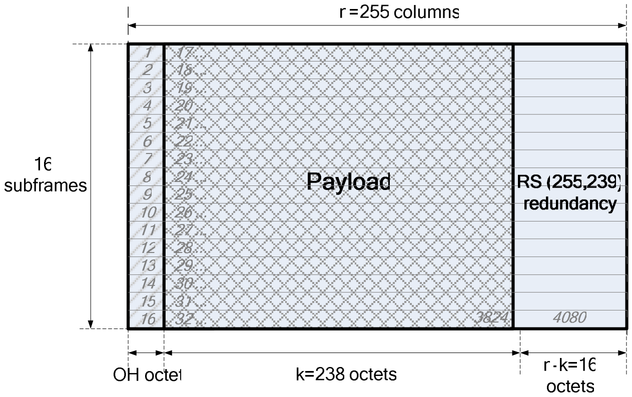

Fig. 2. The structure of one row of the OTU frame.

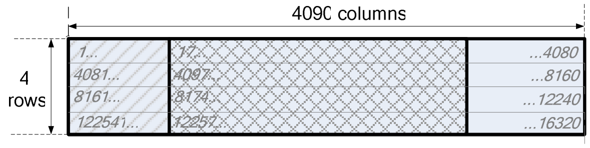

Fig. 3. The structure of the OTU frame.

10Gb Ethernet packets, although the full compatibility is not provided. On the other side, in contrary to SDH networks, with the increase of the throughput frame duration is decreased as the transmission frame size remain unchanged in all OTH hierarchy levels (4080 columns x 4 rows).

TABLE II
THE OTH THROUGHPUTS

SDH (IEEE G707)	OTH (IEEE G709)	Line data rate in OTH (Mb/s)	Information data rate in OTH (Mb/s)	OTU frame duration (μs)
STM-16	OTU-1	2666.06	2488.32	48.97
STM-64	OTU-2	10709.23	9953.28	12.19
STM-256	OTU-3	42836.90	39813.12	3.04

III. THE OPTICAL TRANSPORT SYSTEM CAPACITY

As it is already mentioned, capacity of WDM system can be calculated as a summation of individual channels capacities (in different wavelengths). In this section, we will calculate the capacity of every individual channel denoted by C, and present it normalized to bandwidth B.

In the next sections, we will assume that the symbol at the input of any individual channel in WDM multiplex can take values from the finite set, described by the constellation points. If the constellation points are denoted by $a^{(k)}$, k=1,2,...M, and x represents the send signal in the time instant of interest, we can write

$$x \in \left\{ a^{(1)}, a^{(2)}, \ldots, a^{(M)} \right\}. \tag{1}$$

On the other side, it will be assumed that the decision in the receiver will be made according to the “soft decision” principle. Therefore, although the signal at the channel input has a discrete constellation, the constellation of the signal at the channel output is continual by nature and it is not compared with fixed region bounds.

Let $P(a^{(k)})$ denotes the a priory probability for k-th elementary signal at the channel input (that corresponds to one of the constellation points), while $p(y/a^{(k)})$ denotes the conditional probability density function (PDF). The last defined quantity determines the probability that send signal $a^{(k)}$ produce received signal y, that can take all possible (continual) values in range (-∞,∞). It is well known that the capacity of this channel, for the case when the channel is memoryless, can be calculated according to formula [10]

$$C/B = \max_{P(a^{(1)}),\ldots,P(a^{(M)})} \sum_{k=1}^{M} P(a^{(k)}) \int_{-\infty}^{\infty} p(y/a^{(k)}) \times \mathrm{ld} \left\{ \frac{p(y/a^{(k)})}{\sum_{i=1}^{M} P(a^{(i)}) p(y/a^{(i)})} \right\} dy. \tag{2}$$

Problem of the above expression optimization for the case of one-dimensional constellations are analyzed in details by Wozencraft and Jacobs [10], and final solution for the case of two-dimensional constellations is given by Ungerboeck in his famous paper [11]. For the practical purposes, it is extremely important that a priory probability that corresponds to constellation point are equal $\{P(a^{(k)})=1/M, k=1,2,\ldots,M\}$.

The first realized optical systems used the *Intensity Modulation with Direct Detection* (IMDD), also known as *On-Off Keying* (OOK). Although this solution results in reduced spectral efficiency, it is still very popular in low-cost optical networks. This modulation type, described by one-dimensional constellations, had not shown enough efficiency for high-speed transmission (>10Gb/s), where non-linear effects highly degrade amplitude of the received signal. Therefore, the contemporary optical systems usually use coherent phase modulations. Simpler solutions are applied in systems based on differential phase modulation (DPSK) and differential quaternary phase modulation (DQPSK), with non-coherent detection [3, 12]. Recently, systems with multilevel modulation and coherent detection are proposed [13], as a tool for the significant increase of the spectral efficiency.

If we assume that only the noise resulted from *Amplified Spontaneous Emission* (ASE) effect in optical amplifiers is present in the optical channel, in the first approximation we can assume that the probability density function $p(y/a^{(k)})$ is Gaussian. In this special case, the channel capacity for two-dimensional constellations is determined by expression [11]

$$\frac{C^*}{B} = \log_2 M - \frac{1}{M} \sum_{k=1}^{M} E \left\{ \log_2 \sum_{i=1}^{M} \exp \left[-\frac{\left| a^{(k)} + n - a^{(i)} \right|^2 - |n|^2}{2\sigma^2} \right] \right\}. \tag{3}$$

The measurements in available optical systems show that, with throughput of 10 Gb/s, the intersymbol interference due to chromatic aberration also exist in the channel. With throughputs greater than 40 Gb/s, due to high nonlinearity if optical fiber it cannot be neglected cross-talk inside the channel and between the channels (IXPM - *Interchannel Cross-Phase Modulation between pulses*, IFWM -

Interchannel Four-Wave Mixing), and *Polarization Mode Dispersion* (PMD) [2,4,12].

In the available literature, it can be found several approaches for the design of simulation model that could take into the account all mentioned channel effects. In paper [14] these effects are jointly modeled using the channel with memory (impact of the intersymbol interference), and in paper [15] the more sophisticated simulation model that include most of the mention effects is developed.

In this paper, we concentrate to the channel model that could be used for efficient calculation of the channel capacity and Monte Carlo simulation on the basis of modulation channel. This model could be used for the estimation of the bit error probability, when the modulation and error control code parameters are defined. For this purpose, it is necessary to know a-posteriori probability density function for the corresponding channel, denoted by $p(y/a^{(i)})$ and defined in eq. (2). The measurement results in previously realized optical systems have shown that $p(y/a^{(i)})$ in this case does not perfectly fit to normal (Gaussian) distribution. For the data rate less than 10 Gb/s, the dominant interference is due to the chromatic dispersion, and channel can be described using asymmetric Gaussian distribution [16]. More precise results could be obtained if the received signal is described by chi-quadrate distribution [17].

On the other side, as a quality measure in optical channel, it is usually used the Q-factor (instead of signal-to-noise ratio). This quantity takes into account noise as well as the other effects that degrade the optical transmission. For various conditional PDFs $p(y/a^{(k)})$, that can even be different for individual constellation points $a^{(k)}$, we can always determine corresponding mean values μ_k and standard deviations σ_k. For the case of binary intensity modulation, the Q-factor is defined by expression [2]

$$Q = \frac{\mu_1 - \mu_2}{\sigma_1 + \sigma_2}, \tag{4}$$

and similar identities can be written for the case of the multilevel modulations. In paper [14], it is described how the variables necessary for calculation of Q-factor can be experimentally determined, when sum of the noise and the overall and interference is chi-square distributed. The first step in the capacity calculation is generation of the complex Gaussian noise with enough size. The summation of quadrate values of the every sample real and imaginary parts is chi-quadrate distributed, and it can be used for statistical averaging of the channel output signal.

In Fig. 5, the capacity that corresponds to the system where M-PSK constellation is applied (for the cases M=2, 4, 8 and 16). It can be noticed that for the bit error rate BER=10^{-6}, using 16-PSK, the spectral efficiency 4b/s/Hz can be achieved for Q-factor of 21dB, while the intensity modulation with sixteen levels (16-IMDD) require Q factor of 29dB, for the same spectral efficiency.

On the other side, the Shannon formula anticipate that the same spectral efficiency (with arbitrary low bit error rate during transmission) can be achieved for Q=12dB. In Fig. 4, it is also shown the bound that corresponds to approximate expression for system capacity, when number of the M-PSK constellation points grows toward the infinity. It is known that, for the greater values of Q-factor (or the signal-to-noise ratio) capacity can be approximated with expression [12]

$$C/B \le ld(Q)/2 + 1.1\,. \tag{5}$$

It is clear that the gap between the Shannon capacity (without a limitation to constellations with the same average power) and capacity for M-PSK given with the above expression became wider for the greater spectral efficiency. For the case of the intensity modulation, this effect became more noticeable.

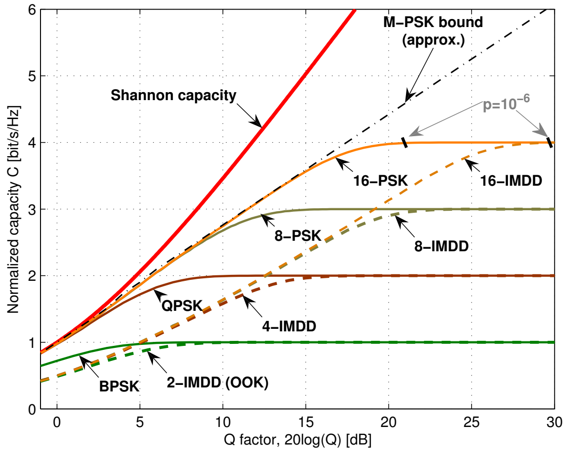

Fig. 4. Channel capacity in WDM system with intensity and M-PSK modulation.

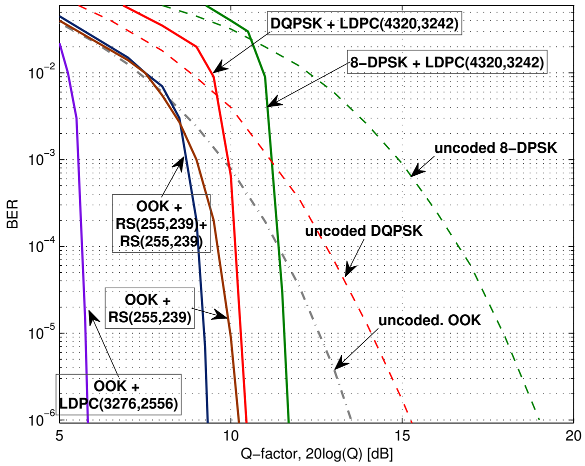

Fig. 5. Performance of WDM system with binary intensity and DPSK modulation.

IV. THE EFFICIENCY OF ERROR CONTROL CODES IN THE OPTICAL TRANSPORT SYSTEMS

In the previous section, estimation of the optical transport system capacity is performed for the case when the noise and chromatic dispersion is present. It is also assumed when the transmission is based on (binary or multilevel) intensity modulation or on M-PSK modulations with constant transmit power. In this section, performances of the OTH optical transport systems are considered for the specified modulation formats.

The bit error rate represents typical performance measure, and in this section it is estimated using Monte Carlo simulation. In simulation, the information blocs with size of 810 bytes (corresponds to payload and header in STM-0 frame) are generated, as it is shown in Fig. 1. For the system with the binary intensity modulation (OOK) with applied error control code (n,k), this sequence is repacked in the structure shown in Fig. 2. We assume that it is not necessary to keep parameters n=255 and k=239, but all the other parameters of the OTU frame remain unchanged. Finally, the binary sequence is transformed into unipolary signal without return to zero (*Not Return to Zero* - NRZ). Then, according to described simulation model, the additive Chi-Square distributed interference (that model the influence of ASE and the chromatic dispersion) is generated and added to NRZ signal. At the receiver, the "direct detection" principle is applied [2].

The numerical results are obtained using the estimation in N=1000 transmitted STM-1 frames and presented in Fig. 5. If we apply RS(255,239) code (recommended by standard [9]), the coding gain of 4dB is detected for on-off keying and the error rate BER=10^{-6}. However, for the code rate R=0.93 and OOK modulation, this result is more than 5dB away from Shannon bound!

Additional improvement can be achieved using the concatenation of RS code, and the LDPC(3276,2586) code achieve coding gain of 9dB, about 2dB away from the Shannon bound that correspond to the code rate R=0.79.

We further considered the combination of the error control code LDPC(4320,3242) and M-PSK modulations with non-coherent detection, proposed in paper [12]. The corresponding numerical results are presented in Fig. 5. The most interesting results are obtained for coded 8-DPSK, where, for error rate BER=10^{-6}, the coding gain of 7dB is achieved compared to the uncoded 8-DPSK, and about 3dB compared to the uncoded DQPSK. In this system, for the reason of non-coherent detection, spectral efficiency of 2b/s/Hz is achieved for Q-factor about 6dB greater then minimal theoretical value, determined by the Shannon limit.

V. CONCLUSION

In this paper, the overview of technologies suitable for transmission of packets through optical transport network, and the special attention is dedicated to impact of error control coding techniques use in current systems. We proposed the simulation model, which can be used for modeling of typical imperfections in data transmission through the considered optical WDM system. Using the chosen simulation model, estimation of channel capacity is performed for systems with intensity and phase modulation. Using the simulation model, it has been shown that applying the considered error control codes can simultaneously increase spectral efficiency and reduce bit error rate, improving the service quality in optical transport networks.

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