Calculation of Achievable Information Rates of Long-Haul Optical Transmission Systems Using Instanton Approach

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***Abstract*—A method for estimation of achievable information rates of high-speed optical transmission systems is proposed. This method consists of two steps: 1) approximating probability density functions for energy of pulses, which is done by the instanton approach, and 2) estimating achievable information rates by applying a method originally proposed by Arnold and Pfitser. Numerical results for a specific optical transmission system (submarine system at transmission rate 40 Gb/s) are reported.**

***Index Terms*—Achievable information rates, instantons, optical fiber telecommunication systems, probability density function (pdf), Shannon capacity.**

I. Introduction

OPTICAL FIBER is a low-loss high-capacity cost-efficient transmission media. As rates at which information can be transmitted increase, a fundamental question about physical limitations of optical fiber arises. The nonlinear nature of the propagation of light in optical fiber systems plays a crucial role in limiting the capacity and makes these limits difficult to calculate.

The problem of determining capacity of optical transmission systems has been addressed by numerous researchers. For example, Mitra and Stark [1] approximated a nonlinear noisy channel by a linear one with an effective nonlinear noise. Such an approach, as indicated in [2], is valid only for specific transmission systems. In dispersion-free transmission [3], [4], the nonlinear Schrödinger equation (NLSE) can be solved analytically, but such results are only of academic interest since a dispersion-free fiber is still not widely available. The results obtained by Tang in [5] are based on solving the NLSE by Volterra series expansion up to the first order. The channel capacity is determined using the Pinsker's formula, which is valid only if noise is Gaussian. The properties of optical transmission in an analog noisy nonlinear channel with weak dispersion management, zero average dispersion, and unlimited power was considered by Turitsyn *et al.* in [2].

We investigate single mode systems with return-to-zero (RZ) pulses (with the same phase) and erbium-doped fiber amplifiers (EDFA). Data are encoded by presence (or absence) of a pulse in a bit slot (ON–OFF keying).

Following the approach from our recent publication [6], we use a method based on Bahl–Cocke–Jelinek–Raviv (BCJR) algorithm [7] originally proposed in the context of magnetic channels (see [8] and [9]). This method is centered around probability density functions (pdf) of the energy at a bit slot given bit configuration surrounding that slot. In [6], those functions were numerically approximated in the form of histograms, but the calculations were computationally extensive, and the results were very sensitive to the precision of calculation of pdfs. For details and problems with histogram approach, see [10].

In this paper, we derive analytical estimates for those pdfs. Most of the previously derived analytical approximations for the pdfs follow the approach in [11], where the Nyquist–Shannon sampling theorem is used to present pdfs as a sum of squared Gaussian variables, therefore resulting in χ^2 distributions. Here, we take a different approach and estimate pdfs by the method of optimal fluctuations [19] or instantons [20]. Our approach is very similar to saddle point approaches used in [12] and [13], among others. However, we calculate the saddle point, which is "the most damaging" noise configuration, analytically. Motivation to use this method comes from the fact that bit errors in modern optical transmission systems are very rare. The statistics of rare events are dominated by contributions from very specific randomness realizations (optimal fluctuations). The concept of optimal fluctuations was first developed in the context of condensed matter physics; recently, it has been successfully applied to evaluation of the efficiency (bit error rate) of forward-correction codes [20].

In the numerical results section of this paper, we apply the proposed method on a realistic optical communication system. This is a submarine system that belongs to the class of dispersion-managed systems, where pieces of optical fiber with positive (anomalous) and negative (normal) dispersion are periodically incorporated.

We estimate an achievable information rate of a high-speed (40 Gbs/s) long-haul optical transmission with an independent uniformly distributed (i.u.d.) source when the combined

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effects of amplified-spontaneous-emission (ASE) noise, Kerr nonlinearity, stimulated Raman scattering (SRS), and chromatic dispersion (group velocity dispersion (GVD), and second-order GVD) are considered.

II. Information Rate and Capacity for Optical Transmission Systems

An optical transmission system (channel) is modeled as an intersymbol interference channel, where m bits on both sides influence the observed bit. The fact that the observed bit depends on the bits from both sides is one of the differences between optical channels and magnetic channels ([8] and [14]), where only bits on one side influence the observed bit's value.

A communication channel is described by the conditional density function of the channel output vector $y = (y_1, \ldots, y_n)$ with $y_i \in Y$, given the channel input (source) vector $x = (x_1, \ldots, x_n)$ with $x_i \in X$. In our case, inputs are binary, that is, $X = \{0, 1\}$. The channel is completely defined by X, Y, and the conditional probability function $P(\mathbf{Y}|\mathbf{X})$. We shall use X_i^j to denote $(X_i, \ldots, X_j)$.

Information rate is defined as

$$I(Y; X) = H(Y) - H(Y|X) \tag{1}$$

where $H(U)$ is entropy defined as $H(U) = -E(\log_2 P(U))$ for a random variable U. Channel capacity is defined as

$$C = \max I(Y; X) \tag{2}$$

where the maximization is performed over all possible input distributions.

One way of achieving performance close to channel capacity, in a channel with memory (as optical channel), is to use nonlinear codes (see, for example, [17]). Here, we address a problem often encountered in practice: calculating information rate in the case of independent and uniformly distributed (i.u.d) channel input source. Therefore, we calculate a lower bound on the channel capacity.

Shannon–McMillan–Breiman theorem [18] gives that

$$\lim_{n\to\infty} \frac{1}{n} \log_2 P(Y_1^n) = E\left(\log_2 P(Y)\right), \qquad \text{with probability 1.}$$

Therefore, the problem of estimating the information rate given by (1) can be reduced to generating a long sequence y_1^n and calculating $\log_2 P(y_1^n)$.

Expression (1) reduces to

$$I(Y; X) = \lim_{n\to\infty} \frac{1}{n} \left[\sum_{t=1}^{n} \log_2 P\left(y_t | y_1^{t-1}, x_1^n\right) - \sum_{t=1}^{n} \log_2 P\left(y_t | y_1^{t-1}\right) \right]. \tag{3}$$

To calculate an estimate of $P(y_t|y_1^{t-1})$, we use a variant of the BCJR algorithm [7].

Bit configurations (states) can be ordered corresponding to integer value of states seen as binary numbers. We shall refer to states by their index, i.e., state s_t shall be referred to as t.

The forward recursion of the BCJR algorithm is a computation of $P(y_t|y_1^{t-1})$ for $t = 1, \ldots, n$ given by

$$P\left(y_t|y_1^{t-1}\right) = \sum_{i,j} \alpha_{t-1}(i) P_{ij} P(y_t|j)$$

$$\alpha_t(s) = \frac{\sum_i \alpha_{t-1}(i) P_{is} P(y_t|s)}{\sum_{i,j} \alpha_{t-1}(i) P_{ij} P(y_t|j)}$$

where the posterior source/channel state probability mass function $\alpha_t(s)$ is defined as

$$\alpha_t(s) = P\left(S_t = s | Y_1^t = y_1^t\right).$$

The factor P_{ij} is a probability of transition from i to j. In the case of binary i.u.d. source, it is 1/2 for two possible transitions and zero for others. Probability functions $P(y_t|j)$ come from the physical properties of the channel and depend directly on the pdfs $p(y|j)$ that shall be derived in the next section.

Before we move further, note that the second term from (3) $P(y^t|y_1^{t-1}, x_1^n)$ is exactly equal to $P(y_t|x_{t-m}^{t+m})$ if independence of the noise at different bit locations is assumed. Therefore, once we know pdfs, we can determine an estimate for the information rate.

III. PDFs by Using Instanton Approach

According to the central limit theorem, short correlated ASE noise at the position z in the moment t, which is $\xi(t, z)$, can be considered to be Gaussian with zero mean and uncorrelated (time in which noise from EFDA is correlated is short even compared with the duration of the bit slot [21]):

$$\langle \xi(t_1, z)\xi(t_2, z)\rangle = N\delta(t_1 - t_2)$$

where N is noise intensity, and correlation is denoted by $\langle\ \rangle$. We assume that noise statistics do not depend on transmitted pulses.

We consider that propagation of noise through fiber is governed by

$$i\vartheta_z(t, z) + u'(z)\vartheta_{tt}(t, z) = i\xi(t, z). \tag{4}$$

Nonlinear interaction of the noise is neglected. The dispersion map function is $u'(z)$, and $\vartheta(t, 0) = 0$.

Solution of (4) is

$$\vartheta(t, z) = \int_0^z \int_R G(t - s, y)\xi(s, y)\, ds\, dy$$

where the Green's function of the linear operator $i\partial_z + u'(z)\partial_t^2$ is given by

$$G(t, z) = \frac{\exp\left(\frac{it^2}{4[u(z)-u(0)]}\right)}{\sqrt{4\pi i\, [u(z) - u(0)]}}.$$

Taking into account that

$$\lim_{u(z_1)\to u(z_2)} \frac{\exp\left(\frac{i(t_1-t_2)^2}{4[u(z_1)-u(z_2)]}\right)}{\sqrt{4\pi\left[u(z_1)-u(z_2)\right]}} = \delta(t_1-t_2)$$

it can be obtained that

$$\lim_{u(z_1)\to u(z_2)} \langle \vartheta(t_1,z_1), \vartheta(t_2,z_2)\rangle = Nz\delta(t_1-t_2). \tag{5}$$

The pdf of the energy at the center slot is

$$p(E|s) = \left\langle \delta\left(E - \int_{-T/2}^{T/2} |A_s(t,z)+\vartheta(t,z)|^2\, dt\right)\right\rangle_{\vartheta} \tag{6}$$

where T is the size of a time slot, s is a bit configuration surrounding the center bit that gives $A_s(t,z)$ via nonlinear interaction of the pulses in the absence of noise, and $\delta(\cdot)$ stands for the delta function. Averaging $\langle\rangle_\vartheta$ is done over all noise configurations.

Taking into account (5), (6) can be rewritten as

$$\begin{aligned} p(E|s) = \int d\lambda \int D\vartheta \exp\left(-\frac{1}{2Nz}\int_{-T/2}^{T/2} |\vartheta|^2 dt\right) \\ \times \exp\left(-i\lambda\left(E - \int_{-T/2}^{T/2} |A_s(t,z)+\vartheta(t,z)|^2\, dt\right)\right) \end{aligned} \tag{7}$$

where D denotes path integral.

This integral can be estimated by evaluating it around its saddle point(s) (optimal fluctuations). Denoting

$$\Phi = \left(-\frac{1}{2Nz}\int_{-T/2}^{T/2} |\vartheta|^2 dt - i\lambda\left(E - \int_{-T/2}^{T/2} |A_s+\vartheta|^2 dt\right)\right)$$

we have

$$\begin{aligned} \frac{\delta\Phi}{\delta\vartheta} &= 0 \\ \frac{\delta\Phi}{\delta\vartheta^*} &= 0 \\ \frac{\partial\Phi}{\partial\lambda} &= 0 \end{aligned}$$

where δ denotes functional derivative.

This system of equations gives

$$\begin{aligned} -\frac{1}{2Nz}\vartheta^* + i\lambda(A_s^*+\vartheta^*) &= 0 \\ -\frac{1}{2Nz}\vartheta + i\lambda(A_s+\vartheta) &= 0 \\ E - \int_{-T/2}^{T/2} |A_s+\vartheta|^2 dt &= 0 \end{aligned} \tag{8}$$

for all $t \in [-T/2, T/2]$.

This system has only one solution for ϑ given by

$$\vartheta = \frac{2i\lambda Nz}{1-2i\lambda Nz} A_s. \tag{9}$$

This is the noise configuration that has the greatest influence on energy of the received pulse. It is not surprising that it has the same shape as the pulse A_s.

From the system (8), we get

$$|\vartheta + A_s|^2 = \left|\frac{2i\lambda Nz}{1-2i\lambda Nz}A_s + A_s\right|^2 = \frac{|A_s|^2}{(1-2i\lambda Nz)^2} \tag{10}$$

for all $t \in [-T/2, T/2]$. By integrating the last expression and by using the last equation from (8), we get that

$$E = \int_{-T/2}^{T/2} \frac{|A_s|^2}{(1-2i\lambda Nz)^2}. \tag{11}$$

This allows us to express the "optimal" λ in terms of A_s and E

$$2i\lambda Nz = 1 - \sqrt{\frac{\int_{-T/2}^{T/2}|A_s|^2}{E}}. \tag{12}$$

In addition

$$\int_{-T/2}^{T/2} |\vartheta|^2 dt = (2i\lambda Nz)^2 E. \tag{13}$$

Finally, we have the expression for $P(E|s)$. Equation (7) can be estimated by using the last equality from (8) and (12) and (13) as

$$p(E|s) \approx C\exp\left[-\frac{1}{2Nz}\left(\sqrt{E} - \sqrt{\int_{-T/2}^{T/2}|A_s(t,z)|^2}\right)^2\right] \tag{14}$$

where C is the normalization constant.

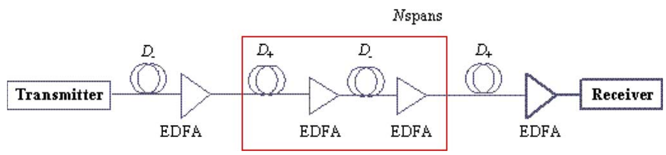

Fig. 1. Scheme of the optical transmission system considered.

Thus, the pdfs are exponential and not Gaussian, as is often assumed in the existing literature. This implies that tails of these functions are very hard to obtain numerically. We note that similar approximations for pdfs have been derived in different ways; see, for example, [10], [23], and [24].

Noise with any statistics can be easily incorporated, as long as it is uncorrelated. The expression $\exp(-(1/2Nz)\int|\vartheta|^2 dt)$ in (3) is a consequence of using Gaussian noise. Noise with different statistics will have an expression other than $\exp(-(1/2Nz)\int|\vartheta|^2 dt)$, reflecting different density. If noise is correlated, expressions for the partial derivatives of Φ become integral equations that need to be solved numerically.

Therefore, instead of running extensive computer simulations to obtain sufficiently precise numerical approximation of the pdfs (as in [6]), herein, we obtain an estimate of achievable information rate as follows.

1) The optical transmission system is simulated in the absence of noise to determine values $\int_{-T/2}^{T/2}|A_s(t,z)|^2$.
2) The system is simulated with noise to obtain sequence y_1^n (the value for n should be $\sim 10^6$ [14]).
3) Estimation for the achievable information rate is obtained from (3) and (14).

IV. Numerical Results

To illustrate the method, we considered the system in Fig. 1. As mentioned in the introduction, this system consists of periodically distributed sections of fiber with positive D_+ and negative dispersion D_- separated by amplifiers (EDFA). One span consists of one section of fiber with positive dispersion, one section of fiber with negative dispersion, and corresponding amplifiers (see Fig. 1).

The transmission of a signal through the fiber is modeled by the NLSE

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial t^3} + i\gamma|A|^2 A \qquad (15)$$

where z is the propagation distance along the fiber, relative time $t = t_{\mathrm{real}} - z/v_g$ gives a frame of reference moving at the group velocity v_g, $A(z,t)$ is the complex field amplitude of the pulse, α is the attenuation coefficient of the fiber, β_2 is the GVD coefficient, β_3 is the second-order GVD, and γ is the nonlinearity coefficient giving rise to Kerr-effect nonlinearities: self-phase modulation, intrachannel cross-phase modulation, and intrachannel four-wave mixing. In short, this calculation takes into account modulation, extinction ratio, realistic models of the transmitter, optical filter and electrical filter, crosstalk effects, Kerr nonlinearities, ASE noise, and dispersion effects (GVD and second-order GVD).

TABLE I
Parameters of the Fibers Used

Parameters	D_+ fiber	D_- fiber
Dispersion [ps/(nm km)]	20	-40
Dispersion Slope [ps/(nm^2 km)]	0.06	-0.12
Effective Cross-sectional Area [μm^2]	110	50
Nonlinear refractive index [m^2/W]	2.2×10^{-20}	2.2×10^{-20}
Attenuation Coefficient [dB/km]	0.19	0.25
Length (in one span) [km]	33.4	16.7

In the system simulator, propagation of pulses through the system, i.e., solving NLSE (15), was done numerically by the split-step Fourier method [22].

The parameters of positive dispersion D_+ and negative dispersion D_- fibers are given in Table I. Precompensation of -330 ps/nm and corresponding postcompensation were also applied. The RZ modulation format has duty cycle of 33%, and the launched power was set to -6 dBm. EDFA with noise figure of 8 dB were deployed after every fiber section, the bandwidth of optical filter was set to $3R_b$, and the bandwidth of electrical filter to $0.65R_b$, with R_b being the bit rate (40 Gb/s).

We first ran the system simulator without noise and with random bit sequence to obtain values $E_s = \int_{-T/2}^{T/2}|A_s(t,z)|^2$ needed in the pdfs (14). Length of the bit configurations s was 7 bits. The strength of the map described above is approximately 8, so we calculate the lower bound on the achievable information rate in the case of an i.u.d. source [15].

The nonlinear distance of this system is roughly 6000 km. Since we neglected nonlinear interactions between pulses and noise, the domain of validity of our pdf approximation is less than two nonlinear distances. Discussion on how to improve the pdf so that they are valid for longer distances is outside of the scope of this paper and shall be presented elsewhere [25]. In the Fig. 2, we compare pdfs proposed in this paper with histograms used in [6] for two bit configurations: 1) with zero in the center slot $s = 0110110$ and 2) with "1" at the center slot $s = 0001000$. Both bit configurations were propagated through 100 spans. Note also that the number of bins used for the histograms affects the entropy.

We then ran the system simulator to obtain sequence y_1^n for different number of spans. BCJR was applied to estimate achievable information rate via (3).

We compare sensitivity of the results to the amplifier noise. Current EDFA introduce noise at levels of 4–8 dB, so we considered these levels. Results are presented in Fig. 3. It can be seen that the achievable information rate is close to one bit per channel use for reasonable distances (total length of one span is 50 km). This implies that no high-redundancy forward error correction code is needed to achieve reliable transmission but only if sophisticated detection techniques such as BCJR or Viterbi algorithm are applied at the receiver end (see [10] and [23]).

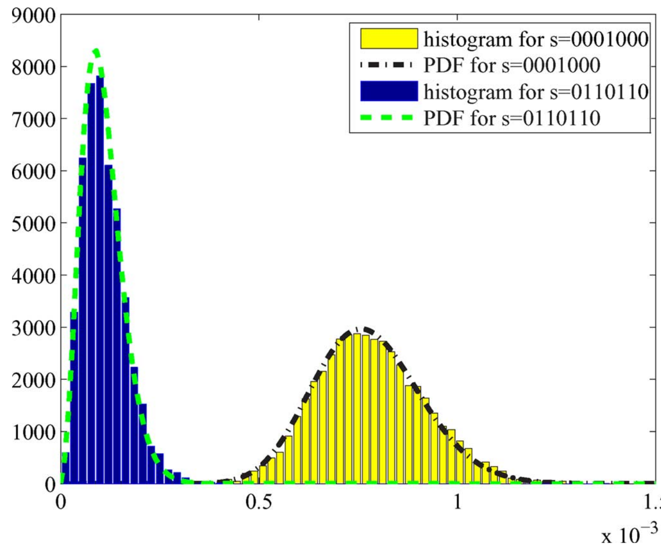

Fig. 2. PDFs after 100 spans.

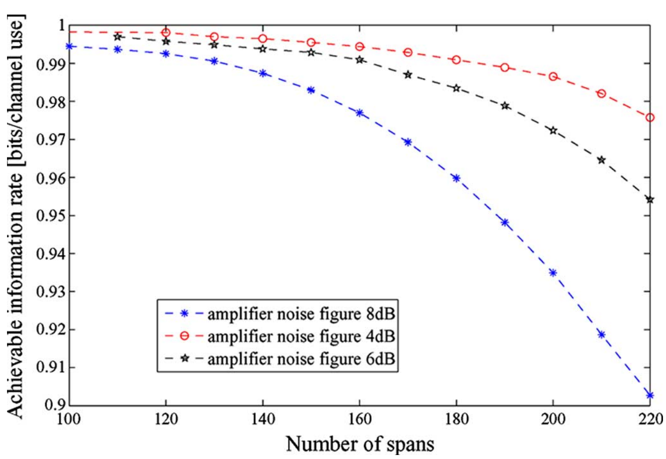

Fig. 3. Achievable information rates for different noise strength.

V. Summary

We present an approach for estimating achievable information rate based on a Monte Carlo method for estimating entropy (originally proposed in [8] and [9]) and an analytical method for estimating channel properties. This is flexible and applicable to a wide range of transmission systems, for example, the same calculations can be repeated for the non-RZ format by numerically calculating energy accumulated at the center slot $\int_{-T/2}^{T/2} |A_s(t,z)|^2$ for bit configurations in this format.

As an illustration, the method was applied to a submarine optical transmission system operating at a transmission rate of 40 Gb/s. Numerical results indicate that with an appropriate receiver and for reasonable distances, this kind of a system can achieve information rates very close to one bit per channel use.

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References

[1] P. P. Mitra and J. B. Stark, "Nonlinear limits to the information capacity of optical fiber communications," *Nature*, vol. 411, no. 6841, pp. 1027–1030, Jun. 2001.

[2] K. S. Turitsyn, S. A. Derevyanko, I. V. Yurkevich, and S. K. Turitsyn, "Information capacity of optical fiber channels with zero average dispersion," *Phys. Rev. Lett.*, vol. 91, no. 20, pp. 203 901.1–203 901.4, Nov. 2003.

[3] J. Tang, "The Shannon channel capacity of dispersion-free nonlinear optical fiber transmission," *J. Lightw. Technol.*, vol. 19, no. 8, pp. 1104–1109, Aug. 2001.

[4] J. Tang, "The multispan effects of Kerr nonlinearity and amplifier noises on Shannon channel capacity for a dispersion-free nonlinear optical fiber," *J. Lightw. Technol.*, vol. 19, no. 8, pp. 1110–1115, Aug. 2001.

[5] J. Tang, "The channel capacity of a multispan DWDM system employing dispersive nonlinear optical fibers and an ideal coherent optical receiver," *J. Lightw. Technol.*, vol. 20, no. 7, pp. 1095–1101, Jul. 2002.

[6] I. Djordjević, M. Ivković, B. Vasić, and I. Gabitov, "Achievable information rates for high-speed long-haul optical transmission," *J. Lightw. Technol.*, vol. 23, no. 11, pp. 3755–3763, Nov. 2005.

[7] L. R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal decoding of linear codes for minimizing symbol error rate," *IEEE Trans. Inf. Theory*, vol. IT-20, no. 2, pp. 284–287, Mar. 1974.

[8] D. Arnold and H.-A. Loeliger, "On the information rate of binary-input channels with memory," in *Proc. Int. Conf. Commun.*, Helsinki, Finland, Jun. 11–14, 2001, pp. 2692–2695.

[9] H. D. Pfitser, J. B. Soriaga, and P. H. Siegel, "On the achievable information rates of finite state ISI channels," in *Proc. Globecom*, San Antonio, TX, Nov. 25–29, 2001, pp. 2992–2996.

[10] O. E. Agazzi, M. R. Hueda, H. S. Carrer, and D. E. Crivelli, "Maximum-likelihood sequence estimation in dispersive optical channels," *J. Lightw. Technol.*, vol. 23, no. 2, pp. 749–763, Feb. 2005.

[11] P. A. Humblet and M. Azizoglu, "On the bit error rate in lightwave systems with optical amplifiers," *J. Lightw. Technol.*, vol. 9, no. 11, pp. 1576–1582, Nov. 1991.

[12] C. W. Helstrom and C. L. Ho, "Analysis of avalanche diode receivers by saddlepoint integration," *IEEE Trans. Commun.*, vol. 40, no. 8, pp. 1327–1338, Aug. 1992.

[13] C. L. Ho, "Calculating the performance of optical communication systems with modal noise by saddlepoint method," *J. Lightw. Technol.*, vol. 13, no. 9, pp. 1820–1825, Sep. 1995.

[14] S. Yang and A. Kavcic, "Capacity of partial response channels," in *Handbook on Coding and Signal Processing for Recording Systems*. Boca Raton, FL: CRC, 2004.

[15] D. Arnold, A. Kavcic, H.-A. Loeliger, P. O. Vontobel, and W. Zeng, "Simulation-based computation of information rates: Upper and lower bounds," *IEEE Trans. Inf. Theory*, vol. 52, no. 8, pp. 3498–3508, Aug. 2006.

[16] V. Sharma and S. K. Singh, "Entropy and channel capacity in the regenerative setup with applications to Markov channels," in *Proc. IEEE Int. Symp. Inf. Theory*, Washington, DC, Jun. 24–29, 2001, p. 283.

[17] N. Varnica, X. Ma, and A. Kavcic, "Capacity-approaching codes for partial response channels," in *Handbook on Coding and Signal Processing for Recording Systems*. Boca Raton, FL: CRC, 2004.

[18] T. M. Cover and J. A. Thomas, *Elements of Information Theory*. New York: Wiley, 1991.

[19] I. M. Lifshitz, "Energy spectrum structure and quantum states of disordered condensed systems," *Usp. Fiz. Nauk*, vol. 83, no. 4, pp. 617–663, 1964.

[20] V. Chernyak, M. Chertkov, M. Stepanov, and B. Vasic, "Error correction on a tree: An instanton approach," *Phys. Rev. Lett.*, vol. 22, pp. 228 701/1–228 701/4, Nov. 2005.

[21] *EDFA Noise Gain Profile and Noise Gain Peak Measurements*, Santa Clara, CA: Agilent Technologies. [Online]. Available: http://cp.literature.agilent.com/litweb/pdf/5963-7148E.pdf

[22] G. P. Agrawal, *Nonlinear Fiber Optics*. San Diego, CA: Academic, 2001.

[23] T. Foggi *et al.*, "Maximum likelihood sequence detection with closed-form metrics in OOK optical systems impaired by GVD and PMD," *J. Lightw. Technol.*, vol. 24, no. 8, pp. 3073–3087, Aug. 2006.

[24] M. R. Hueda, D. E. Crivelli, and H. S. Carrer, "Performance of MLSE-based receivers in lightwave systems with nonlinear dispersion and amplified spontaneous emission noise," in *Proc. IEEE GLOBECOM*, Nov. 29–Dec. 3 2004, vol. 1, pp. 299–303.

[25] M. Ivkovic *et al.*, *Modeling Errors in Long-Haul Optical Fiber Transmission Systems by Using Instantons and Edgeworth Expansion*. in preparation.

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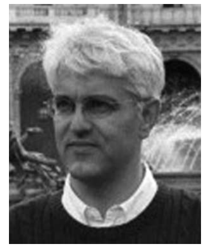

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