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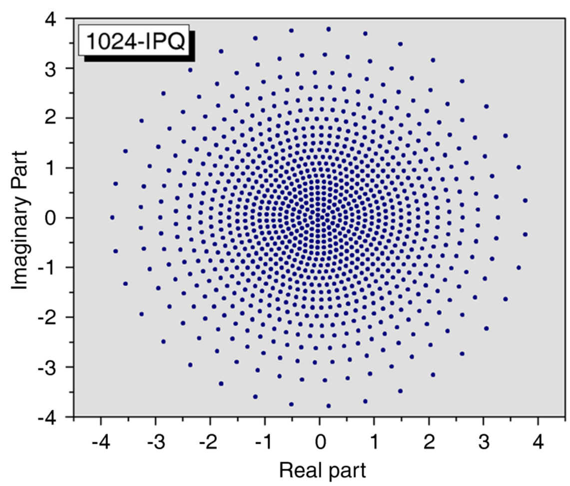

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Iterative Polar Quantization-Based Modulation to Achieve Channel Capacity in Ultrahigh-Speed Optical Communication Systems

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Abstract: In this paper, we propose a nonuniform coded-modulation format based on iterative polar quantization (IPQ) as a scheme to enable achieving channel capacity in ultrahigh-speed optical communication systems. The proposed modulation format is coded with structured low-density parity-check (LDPC) codes optimized for Gaussian channels and, in combination with polarization-multiplexing, can achieve 800 Gb/s per wavelength aggregate rate and beyond utilizing the currently available components operating at 50 GS/s. Using coded IPQ, we show that we can achieve capacity for signal-to-noise ratios (SNRs) of up to 25 dB and increase the total propagation distance over optical transmission systems by 275 km over coded star-quadrature amplitude modulation (QAM).

Index Terms: Coded modulation, coherent communications, fiber optics and optical communications, forward error correction, iterative polar quantization (IPQ), low-density parity-check (LDPC) codes, modulation.

1. Introduction

Channel capacity is defined as the maximum information rate that a communication channel can carry within a given bandwidth [1]. Approaching channel capacity has been one of the major topics of interest for many researchers for decades [2]. Forward error-correction (FEC) codes were introduced as a means to closely approach capacity as they improve the bit error ratio (BER) performance of the communication systems. One of the most successful FEC codes in achieving this goal is the low-density parity-check (LDPC) code [3]. Longer LDPC codes with larger girth tend to improve performance, but the relation between the code length and performance is not linear, as we reach a bottleneck where increasing LDPC codes even to an impractical length would not improve the performance of the system in a noticeable manner. In such cases, a better modulation format would be needed to get closer to achieving capacity. In this paper, and to this end, we propose a nonuniform modulation format based on iterative polar quantization (IPQ) [4] to achieve channel capacity for a given channel using a semianalytical approach, as will be shown later. We present a special case that is optimized for amplified spontaneous emission (ASE) noise-dominated communication channels, where the channel is considered Gaussian. Even though the results throughout this paper are given for this aforementioned channel, that scheme can be adapted to any channel of choice. Using such a modulation format with the aid of a powerful FEC code such as LDPC and polarization-multiplexing, we can achieve an 800-Gb/s aggregate rate and beyond utilizing the currently available components. The proposed modulation format and the transmission rate it offers can be used for high-speed optical communication systems or for future standards of Ethernet. Such rates are needed to keep up with the increasing demand on capacities due to the elevating popularity of the Internet and higher quality multimedia. According to some experts from the industry, the 1-Tb/s transmission should be standardized by 2012–2013 [5].

This paper is organized as follows. The following section describes the IPQ-based modulation format, Section 3 discusses the performance of the proposed format over the ASE noise-dominated channel and over a fiber-optic channel with a standard single mode fiber (SMF) and erbium-doped fiber amplifiers (EDFAs), and finally, the concluding remarks are elaborated in Section 4.

In the case of fiber-optic channels (in Section 3.2), we propose the use of two techniques to further improve the system performance: i) back-propagation and ii) turbo equalization. Coarse digital back propagation with small number of coefficients is utilized to keep the system complexity reasonably low. Meanwhile, turbo equalization is employed to compensate for the remaining channel distortions.

2. IPQ-Based Modulation

The proposed modulation format can be considered as an upgrade for the quadrature amplitude modulation (QAM) or as a generalization of the star-QAM as the constellation points form concentric rings as in a star-QAM [6] but with an irregular yet nonrandom distribution. This format is based on the minimum mean-square quantization error (QMSE) of information, and it takes into consideration the channel to be used and the noise probability density function. In this paper, we focus on one example to show the potential of the scheme: the ASE noise-dominated scenario.

Let us now move to the design of the constellation for the modulation format and explain the theory behind it. As this paper is concerned with the performance of nonuniform signaling, the constellation of the modulation must be selected in accordance with the nonuniform probability distribution of the channel. We know that optimum source distribution for Gaussian channels, such as ASE noise-dominated channels, is Gaussian [1]. The in-phase s_{I} and quadrature s_{Q} components of Gaussian random constellation $\boldsymbol{s} = (s_{\mathrm{I}}, s_{\mathrm{Q}})$ follow a 2-D Gaussian distribution with zero mean. Corresponding polar coordinates of this signal constellation point are given by

$$\boldsymbol{s} = |\boldsymbol{s}|e^{j\theta}, \qquad |\boldsymbol{s}| = \sqrt{s_{\mathrm{I}}^2 + s_{\mathrm{Q}}^2} \quad \theta = \tan^{-1}\frac{s_{\mathrm{Q}}}{s_{\mathrm{I}}} \tag{1}$$

with distribution of envelope $|\boldsymbol{s}|$ being Rayleigh and distribution of θ being uniform.

For a Gaussian source, the distribution of ring radii is selected to be Rayleigh, and the signal constellation is obtained by quantizing the source while minimizing the QMSE. This is achieved using restricted IPQ that consists of a nonuniform scalar quantization of the amplitude and a uniform scalar quantization of the phase. The number of points on each ring is selected iteratively for all the concentric rings, keeping the final number or points for the constellation in mind.

Let L_i denote the number of constellation points per ring of radius m_i, L_r denote the number of rings in the constellation, and L denote the total number of signal constellation points $(L = \sum_{i=1}^{L_r} L_i)$; then, the optimum number of constellation points is determined by [4] as

$$L_i = \sqrt[3]{m_i^2 \int_{r_i}^{r_{i+1}} p(r)\, dr} \Bigg/ \sum_{i=2}^{L_r} \frac{1}{L} \sqrt[3]{m_i^2 \int_{r_i}^{r_{i+1}} p(r)\, dr}, \qquad \text{for } i = 1, 2, \ldots, L_r \tag{2}$$

TABLE 1

Summary of the specifications for the optimum 64-IPQ

Ring index (i)	**1**	**2**	**3**	**4**	**5**	**6**
Lower decision boundary (r_i)	0	0.544	1.019	1.549	2.246	4.5
Ring radius (m_i)	0.334	0.780	1.263	1.835	2.614	
Number of points on the i^{th} ring (L_i)	5	11	15	17	16	

TABLE 2

Summary of the specifications for the optimum 128-IPQ

i	1	2	3	4	5	6	7	8
r_i	0	0.428	0.777	1.160	1.616	2.238	4	4.5
m_i	0.270	0.608	0.966	1.374	1.880	2.612	3.903	
L_i	6	13	20	26	30	28	5	

where $p(r)$ is Rayleigh distribution function

$$p(r) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}}, \qquad \text{for } r \geq 0 \tag{3}$$

and σ^2 in (3) represents the source power.

The radius of ith ring is determined by [4] as

$$m_i = 2\sin(\Delta\theta_i/2) \int_{r_i}^{r_{i+1}} rp(r)\,dr \bigg/ \Delta\theta_i \int_{r_i}^{r_{i+1}} p(r)\,dr, \qquad \Delta\theta_i = \frac{2\pi}{L_i} \quad i = 1, 2, \ldots, L_r. \tag{4}$$

The limits of integration in (2) and (4) are determined by

$$r_i = \pi\left(m_i^2 - m_{i-1}^2\right)/2[m_i L_i \sin(\Delta\theta_i/2) - m_{i-1} L_{i-1} \sin(\Delta\theta_{i-1}/2)], \qquad i = 1, 2, \ldots, L_r. \tag{5}$$

As the rather quick iteration process goes, the number of rings, the radius of each ring, and the number of point on each ring are found. As discussed earlier, the phase distribution is uniform, hence all the information needed for the design are summarized in (2)–(5).

To further improve the performance of the proposed modulation format, structured LDPC codes [7] are used to encode the data before modulation. Structured LDPC codes tend to reduce the encoding complexity in comparison with the random codes as encoding is done using linear shift register circuitry. Moreover, they have been proven to work very well without suffering from the error-floor phenomenon, even for BER lower than 10^{-9} [8].

As basic examples, Tables 1 and 2 summarize the details of the constellations for 64-IPQ and 128-IPQ, respectively.

Fig. 1 shows the 64-IPQ signal constellation in Table 1 as it illustrates the notation. Fig. 2, on the other hand, shows the IPQ constellations for 256 points and 1024 points. As noticed from these figures, the distribution of the points is nonuniform, and it forms a 2-D Gaussian distribution with zero mean. Toward the edges of the constellation the density is minimal, and therefore, the distance between the constellation points is higher. As we go toward the center of the constellation, the density of constellation points keeps increasing till reaching its peak the innermost ring.

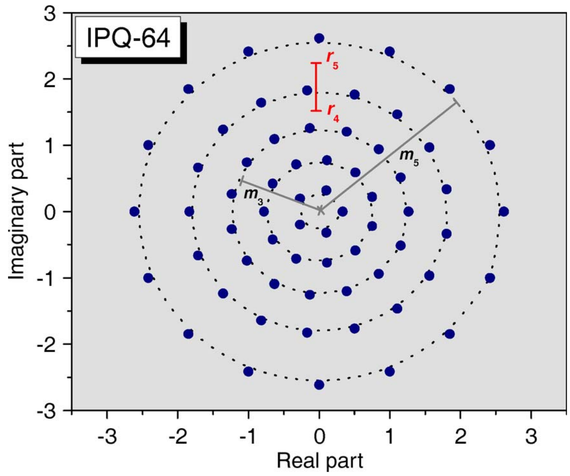

Fig. 1. 64-IPQ signal constellation.

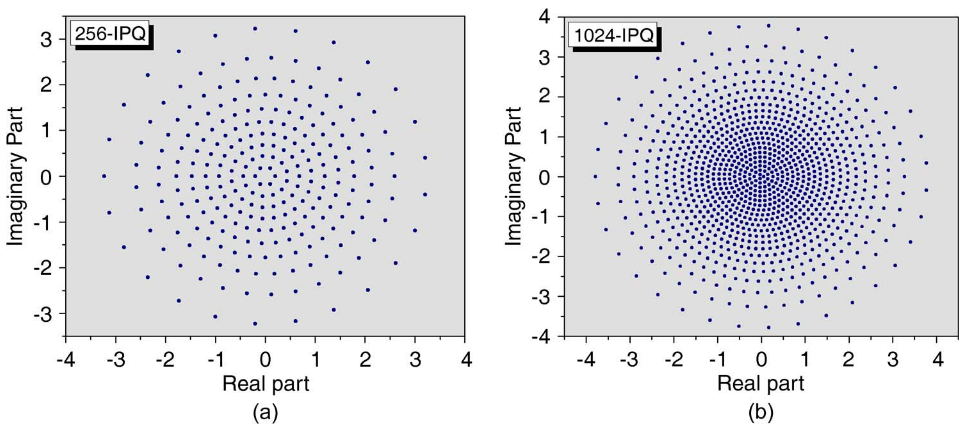

Fig. 2. IPQ signal constellations. (a) $L = 256$ and (b) $L = 1024$.

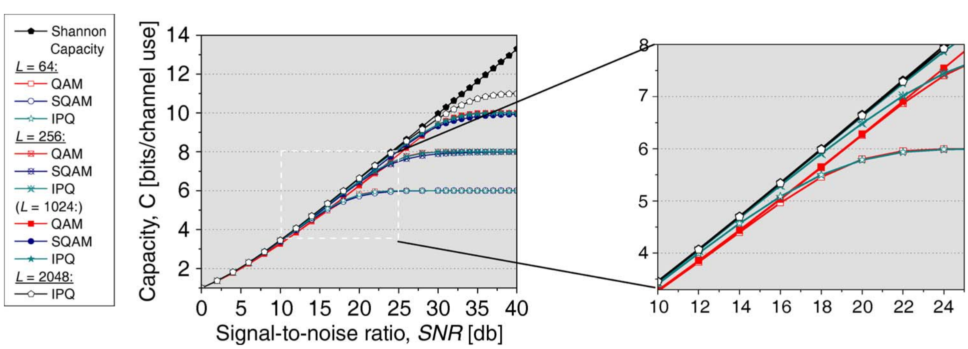

Fig. 3. Channel capacity per single polarization of IPQ modulation versus QAM and star-QAM.

Fig. 3 shows the channel capacity for various values of L and different modulation formats. The figure is obtained by calculating the average information rates (AIRs) over the AWGN channel and assuming equal *a priori* probability for the input symbols. In the figure, we can see that IPQ constellation achieves channel capacity for low and medium signal-to-noise ratios (SNRs) and

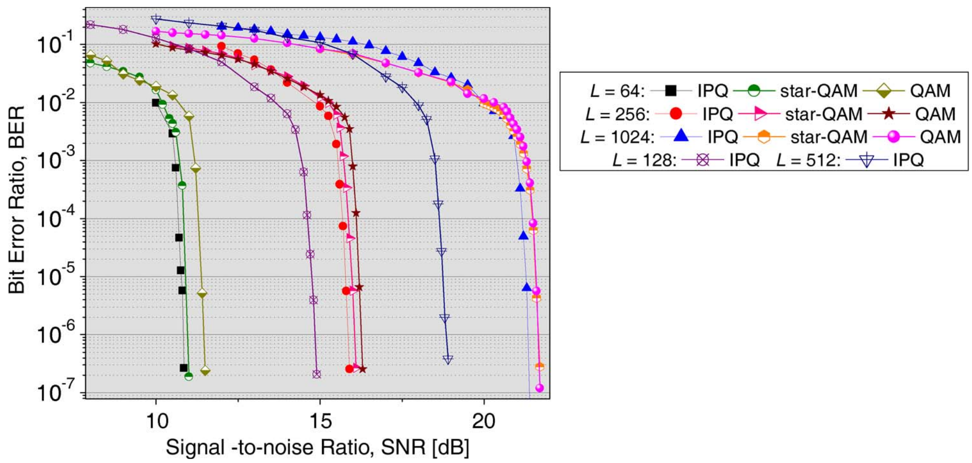

Fig. 4. BER performance for LDPC-coded IPQ, QAM, and star-QAM for different constellation sizes.

significantly outperforms QAM and star-QAM formats. In this figure, we see that IPQ-2048 achieves capacity for up to SNR of 25 dB. This modulation is achieved by a constellation consisting of 28 concentric rings.

The given example with the previously explained steps to achieve capacity can be generalized to match any type of communication channel. In general, the optimum source distribution for a communication channel such as a channel with nonlinearities might not be represented in a simple form like a Gaussian function. In this case, numerical approaches such as those presented in [9] are used to find the optimum source. After finding the optimum source distribution for the channel, the coordinates of the constellation can be found using the IPQ method.

3. Performance Analysis

3.1. ASE Noise-Dominated Channel

The simulations are done over an ASE noise-dominated channel (done by ASE noise loading to the transmitted signal) by using LDPC (16935, 13550), with a rate of 0.8 and girth of 10. The decoding algorithm used is based on the min-sum with-correction-term algorithm [10] with 25 iterations. In these simulations, by using polarization-multiplexing and assuming that the Jones matrix is known on receiver side, the actual effective information rate $(AEIR)$ of the system while using 50 GS/s ranges between $2 \times 6 \times 50 \times 0.8 = 480$ Gb/s for the 64-IPQ and $2 \times 10 \times 50 \times 0.8 = 800$ Gb/s for the 1024-IPQ. The $AEIR$ is calculated as follows: $AEIR = p \times bps \times SR \times r$, where p denotes the number of polarizations, bps denotes the number of bits/symbol, SR denotes the symbol rate, and r denotes the code rate. Utilizing higher rate codes allows a higher actual transmission rate or allows transmission components of lower speeds to achieve the current transmission rate.

The results of these simulations are summarized in Fig. 4. We show the BER performance versus the SNR for the different modulation formats; IPQ, QAM, and star-QAM for constellation sizes of 64, 256, and 1024, in addition to 128 and 512 for IPQ. As shown in the figure, LDPC-coded IPQ outperforms the LDPC-coded square QAM by 0.6 dB, 0.5 dB, and 0.3 dB at a BER of 10^{-6}, for constellation sizes 64, 256, and 1024, respectively, while it outperforms the LDPC-coded star-QAM by 0.2 dB, 0.3 dB, and 0.3 dB for the same constellations. As the constellation size increases the AIR curves of the square QAM and the star-QAM shown in Fig. 3 become closer to achieving capacity for lower SNR values, and this explains why the BER improvement is decreasing as the constellation size is increasing. These results prove that IPQ is the optimum configuration for the signal constellation in terms of matching the ASE noise-dominated scenario.

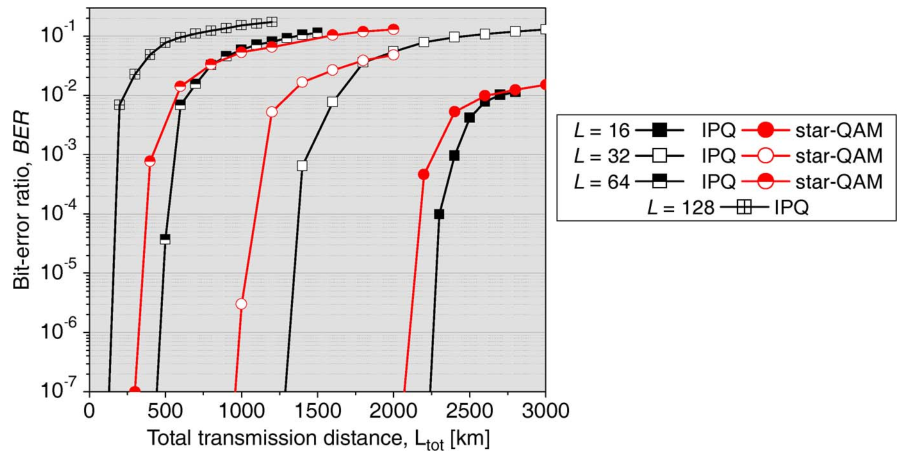

Fig. 5. BER versus total transmission distance.

3.2. Coded IPQ With Digital Back-Propagation and Turbo Equalization

To evaluate the performance of the proposed modulation format over fiber-optic channels, while keeping complexity reasonably low, coarse digital back-propagation [11] with a small number of coefficients, in addition to turbo equalization [8], have been employed. The back-propagation technique is used to lower the required channel memory. This is done by inverting the nonlinear Schrödinger equation (NLSE) by passing the received signal through a fictitious fiber with the opposite signed parameters of the fiber used throughout the transmission system. In the absence of noise, the transmitted signal can always be recovered from the received signal in this manner [11]. Meanwhile, turbo equalization is used to compensate for the remaining channel distortions. This is done by iterating the extrinsic information back and forth between the maximum *a posteriori* (MAP)-based equalizer and the LDPC decoder in a turbo fashion until reaching a maximum number of iterations or converging to recognizable codeword. The bit reliabilities for LDPC decoders are calculated from symbol reliabilities, as described in [8].

Given this general description of the LDPC-coded polarization multiplexed IPQ scheme, Fig. 5 shows the BER results obtained by polarization multiplexed LDPC (8547, 6922)-coded IPQ with digital back-propagation and turbo equalization. The simulations are done for a symbol rate of 50 GS/s and launch power of 0 dBm. The dispersion map is composed of standard SMF (SSMF) only with EDFAs of noise figure of 5 dB deployed every 100 km. The SSMF used in the simulations is with dispersion coefficient of 16 ps/(nm km) and a dispersion slope of 0.08 $\text{ps}/(\text{nm}^2\ \text{km})$. The effective cross-sectional area is of 80 μm^2, the nonlinear refractive index is $2.6 \times 10^{-20}\ \text{m}^2/\text{W}$, and the attenuation coefficient is 0.22 dB/km. As shown in the figure, LDPC-coded IPQ allows longer transmission distances than its coded star-QAM counterpart, as it allows 2250 km, 1320 km, 640 km, and 140 km for $L = 16$, 32, 64, and 128, respectively.

4. Conclusion

This paper presents a nonuniform modulation format based on IPQ to achieve channel capacity. This scheme is optimized for ASE noise-dominated channels. The proposed scheme, in combination with polarization-multiplexing, achieves a beyond-800-Gb/s aggregate rate while achieving capacity for up to 25 dB of SNR utilizing the currently available components. We show that L-IPQ-coded modulation outperforms the coded-QAM and star-QAM counterparts to prove that IPQ is the optimum modulation format for ASE noise-dominated channels. Moreover, we show that after evaluating the IPQ scheme for fiber-optic channels, LDPC-coded IPQ achieves an increase in the propagation distance up to 275 km over the LDPC-coded star-QAM. Applying this configuration, and by using polarization-multiplexing, we allow a total aggregate rate of 800 Gb/s per wavelength and beyond, depending on the design of the LDPC code.

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