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Information Theory

Performance of affine geometry low-density parity-check codes in long-haul optical communications

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SUMMARY

In this paper, we investigate the performance of low-density parity-check (LDPC) codes in long-haul optical communication systems for different modulation formats (nonreturn to zero (NRZ), return to zero (RZ), chirped return to zero (CRZ)). We are particularly concerned with high-rate codes based on affine geometries. These codes have large minimum distance and simple iterative decoding algorithms, which make them good candidates for high-speed applications such as optical communications. We consider both bit-flipping iterative decoding and iterative decoding based on min-sum algorithms. We demonstrate a significant performance improvement with respect to the state-of-the-art error control schemes employed in long-haul systems. Contrary to the common practice of considering the performance of error controlling schemes using the AWGN channel assumption, we consider the performance of the proposed LDPC schemes taking into account, in a natural way, all major impairments in long-haul optical transmission such as ASE noise, pulse distortion due to fiber nonlinearities, chromatic dispersion or polarization dispersion, crosstalk effects, intersymbol-interference (ISI), etc. Copyright © 2004 AEI

1. INTRODUCTION

Recently, a number of high-speed long-haul optical communications systems have been demonstrated, commercialized or implemented [1]. Although data flow through these systems has increased tremendously, it has become widely recognized that full utilization of the available bandwidth cannot be achieved without powerful error control schemes.

A significant effort has been made to apply error control techniques to various optical transmission systems starting with Grover's proposal for applying error control codes to improve the performance of dispersion limited lightwave systems with laser impairments [2]. Recently, particularly in transoceanic submarine systems, error-correcting codes such as the Bose Chaudhuri Hocquenghem (BCH) code or the Reed Solomon (RS) code have been selected for implementation [3]. Sab and Lemaire proposed [4] using turbo decoding [5] for the Alcatel long-haul submarine transmission system. However, turbo decoders have high complexity, and developing integrated circuits operating at multi-gigabit per second speeds is a challenging task.

In this paper, we show that error performance and hardware complexity can be improved by using other types of iteratively decodable coding schemes, in particular low-density parity-check (LDPC) codes [6, 9–14]. We are concerned with codes based on finite geometries [6] because they require only simple encoders and we can be assured of large minimum codeword distances. The structure of finite geometry codes is of crucial importance for high-speed implementations, because these codes can lend themselves to encoders that can be realized by shift registers, and

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because they can be decoded using the belief propagation algorithm.

We show that affine geometry LDPC codes provide a significant system performance enhancement with respect to the state-of-the-art error control schemes employed in optical communication systems. An improvement of 3-4 dB over RS(255,239) code, that is 1.5–2.7 dB over RS(255,223) + RS(255,239) (the notation commonly used in optical communications [3, 4]) concatenation scheme, is demonstrated in just a few iterations. The affine geometry code considered outperforms the turbo code based on a product of two BCH (128,113,6) codes proposed in Reference [3] by 0.5 dB.

Contrary to the common practice of considering the performance of error control codes assuming the AWGN channel noise model [3, 4], we use a very realistic simulation model that takes into account in a natural way all major impairments in long-haul optical transmission such as amplifier spontaneous emission (ASE) noise, pulse distortion due to fiber nonlinearities, chromatic dispersion or polarization dispersion, crosstalk effects, intersymbol-interference (ISI) etc. We show that the LPDC codes perform well in the presence of all these impairments, and we are confident in proposing their use in optical communications.

2. SYSTEM DESCRIPTION

In wavelength division multiplexing (WDM) systems, Figure 1 (a), multiple optical carriers at different wavelengths are modulated by using independent electrical signals and then transmitted over the same fiber. The optical signal at the receiver is split into separate channels by using an optical demultiplexer. Dispersion compensators, consisting of an erbium-doped fiber amplifier (EDFA) and dispersion compensating fiber (DCF), are put periodically to compensate the loss and accumulated dispersion of the standard single mode fiber (SMF). The most frequent signal formats are nonreturn to zero (NRZ) and return to zero (RZ), Figure 1 (b). There are several variations of the RZ format. The very popular formats for long-haul transmission are chirped return to zero (CRZ) and carrier-suppressed return to zero (CSRZ). In CRZ, Figure 1 (b), NRZ modulator,

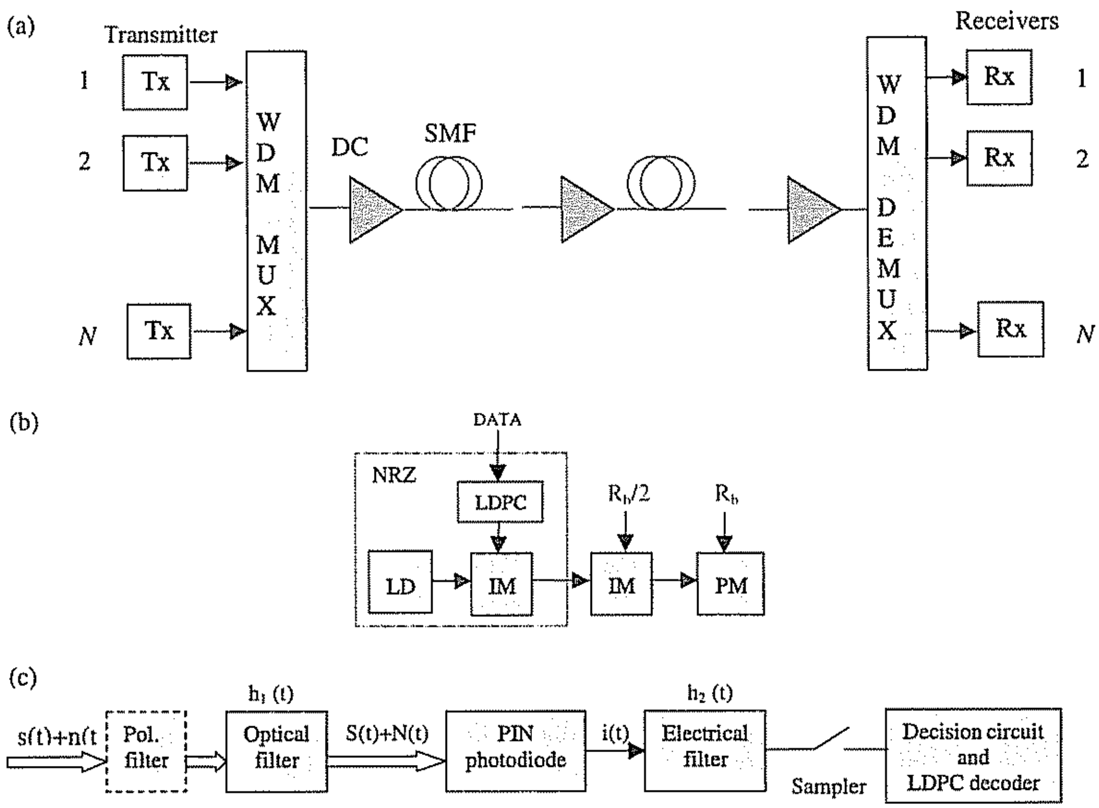

Figure 1 System model (a), chirped return-to-zero (CRZ) transmitter (b) and receiver model (c).

consisting of laser diode (LD), Mach–Zehnder intensity modulator (IM) and LDPC coder, is followed by a push-pull Mach–Zehnder intensity modulator biased at the maximum transmittance with driving signal being a sinusoid at the half-bit-rate frequency. Phase modulator (PM) following IM is driven by a sinusoid at the bit rate frequency. Omitting the PM leads to RZ modulator. (For more details on CRZ reader is referred to Reference [15].) In this configuration, the signal spectral width is controlled by both IM and PM, and the pulse chirping is controlled by the phase modulator and possibly pre-dispersion compensating fiber section. A typical direct detection receiver, Figure 1(c), is composed of a polarization filter, an optical filter of the impulse response $h_1(t)$, a PIN photodiode, an electrical filter of the impulse response $h_2(t)$, a sampler and a decision circuit, followed by an LDPC decoder.

The electrical field coming through the fiber to the optical filter input can be written as

$$e(t) = s(t) + n(t) \qquad (1)$$

where $s(t)$, the (optical) amplifier chain output signal field can be written as

$$s(t) = \sum_{n=-\infty}^{\infty} \sqrt{b_n P} p_n(t - nT_b) \qquad (2)$$

In Equation (2), $p_n(t)$ is the nth bit pulse shape, P is the peak power and b_n is the (coded) information content $b_n \in \{r, 1\}$, with r being the extinction ratio, $0 \leqslant r < 1$. Both the ASE noise components and the multipath interference (MPI) components are combined into a noise process $n(t)$, which is considered to be colored Gaussian with autocorrelation function given by

$$R_n(\tau) = R_{\mathrm{ASE}}(\tau) + R_{\mathrm{MPI}}(\tau) \qquad (3)$$

($R_{\mathrm{ASE}}(\tau)$ and $R_{\mathrm{MPI}}(\tau)$ are ASE and MPI autocorrelaction functions respectively). The power spectral density of ASE noise is determined by the EDFA output filter, while the spectrum of MPI noise is determined by the signal spectrum. The auto correlation function of ASE noise is $R_{\mathrm{ASE}}(\tau) = N_0 R_{\mathrm{EDFA}}(\tau)$, where $R_{\mathrm{EDFA}}(\tau)$ is the EDFA output optical filter autocorrelation function, and N_0 is the power spectral density of ASE noise in one state of polarization (SOP). Within the bandwidth of an optical filter in EDFA, the noise power spectral density function can be approximated as $N_0 \approx n_{\mathrm{sp}}(G-1)hf\, N_{\mathrm{amp}}$, wherein n_{sp} is the spontaneous emission factor, G is the EDFA gain, hf is the photon energy, and N_{amp} is the number of amplifiers. $r(t)$, $s(t)$ and $p_n(t)$ are in fact the complex envelopes of corresponding analytical signals.

The photodiode output noise process has the mean

$$\overline{I(t)} = \int_{-\infty}^{\infty} |S(\tau)|^2 h_2(t-\tau)d\tau + R_N(0) \qquad (4)$$

and the variance

$$\sigma^2(t) = 2R_e\left\{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S(\tau)S^*(\hat{\tau})R_N(\tau-\hat{\tau})h_2 \times (t-\tau)h_2(t-\hat{\tau})d\tau\, d\hat{\tau}\right\} + 2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(t-\tau) \times |R_N(\tau-\hat{\tau})|^2 h_2(t-\hat{\tau})d\tau\, d\hat{\tau} + q\overline{I(t)} + \sigma_e^2 \qquad (5)$$

where $S(t) = s(t) * h_1(t)$ is the optical filter output signal. (The derivation of the Expressions (4) and (5) is given in our previous paper [8].) The autocorrelation function of the optical filter output noise can be expressed as

$$R_N(\tau) = \int_{-\infty}^{\infty} R_{h_1}(t)R_n(\tau - t)dt \qquad (6)$$

where $R_{h_1}(\tau)$ is the optical filter autocorrelation function. Notice that the photodiode output noise process is not stationary (the mean values and the standard deviation are functions of time). In Equation (5) σ_e^2, is the electronic noise variance, which includes both transmitter and receiver electronic noise (also known as 'back-to-back' noise), while $q\bar{I}$ is the photodiode shot noise variance (q is an electron charge). If the polarization filter is omitted, the second term in Equation (5) should be multiplied by a factor of two. The propagation of a signal through the transmission media is modeled by the nonlinear Schrödinger equation. (A discussion of the propagation through a fiber is beyond the scope of this paper, but the reader can refer to Reference [7]). In optical communications, it is a custom to use a Q-factor as a figure of merit rather than signal-to-noise ratio, and in this paper we will follow this convention (more details on calculating the Q-factor in uncoded systems can be found in Reference [8]).

3. CODE CONSTRUCTION

As mentioned in the Section 1, we use affine geometry LDPC codes. The detailed description of these codes can be found in Reference [6]. Here, we summarize their basic structure and properties. The m-dimensional affine geometry, denoted as AG (m, p^s), over GF(p^s) is a set of m-tuples, referred to as points, selected from GF(p^{ms}). Let α be a primitive element of GF(p^{ms}). Then $0, \alpha^0, \alpha^1, \alpha^2, \ldots, \alpha^{p^s-2}$ form the all p^{ms} points of AG(m, p^s).

The p^{ms} m-tuples over GF(p^s), representing the points in AG(m, p^s), form an m-dimensional vector space over

GF(p^s). The one-dimensional subspace is called a line or a block, and the number of points in a line is p^s. The affine geometry has the following properties: any two points are connected by only one line, two lines are either parallel (they do not have points in common) or intersect at only one point. Let us define the point-line incident matrix as a $v \times b$ matrix $H = (h_{ij})$ whose rows correspond to the points and columns to the lines, in which $h_{ij} = 1$ if ith point belongs to jth line. Dimensions of the matrix are $v = p^{sm}$ and $b = p^{s(m-1)}(p^{sm} - 1)/(p^s - 1)$. The matrix has the following properties: its row and column weights are $(p^{ms} - 1)/(p^s - 1)$ and p^s respectively; and the density of ones is $p^{-(m-1)s}$, which is small for $m, s \geqslant 2$. The minimum distance is at least $p^s + 1$. Since any two points are connected by one and only one line, no two rows or columns have more than one '1' in common. Therefore, the point-line incident matrix is in fact the matrix of parity checks of the LDPC code and the corresponding Tanner graph is free of cycles of girth (the length of shortest cycle) 4.

4. DECODING ALGORITHMS

Affine geometries LDPC codes have large minimum distances and their Tanner graph has a girth of six. As shown in References [6, 11–14], they can be decoded by various decoding methods such as one-step majority-logic, bit-flipping and iterative decoding based on the sum-product (message-passing) algorithm. Although sum-product iterative decoding has been demonstrated to perform well in various types of channels, it is computationally intensive and it is not clear if it is suitable for optical communications at data rate 10 or 40 Gb/s or higher. However, the min-sum algorithm, which is an approximation of '*a posteriori*' probability decoding, requires only simple addition and 'finding minimum' operations and, as such, is suitable for high-speed optical transmission. In this paper, we use message-passing based on min-sum approximation and bit-flipping (BF). The BF technique, initially proposed by Gallager [9], is a simple hard-decision iterative decoding technique, and is most suitable for very high speed receiver architectures. The idea behind the BF algorithm is to flip the least number of bits until all parity checks are satisfied or the maximum number of iterations is reached. The min-sum algorithm (MSA) is described in Appendix A.

5. AG LDPC CODE PERFORMANCE

In this section, we present the performance of LDPC codes in the presence of residual dispersion, fiber nonlinearities, ISI and receiver noise resulting from signal–noise and noise–noise interaction in the PIN photodiode. The influence of the transfer functions of the optical and electrical filters is taken into account as well. A WDM system with 10 Gb/s bit-rate per channel and a channel spacing of 50 GHz is considered. It is assumed that the observed channel is located at 1552.524 nm (193.1 THz) and that there exists a nonnegligible interaction with six neighboring channels. The extinction ratio is set to 13 dB. The transmitter and receiver imperfection is described through a back-to-back Q-factor which is set to 23 dB. An affine geometry based LDPC (1056,813) code with code rate of $R = 0.7699$ (redundancy of $\approx 30\%$), constructed as described in Section II for $m = p = 2$ and $s = 5$ ($b = 1056$), is considered.

Figure 2 shows the BER results of a Monte-Carlo simulation. The optical filter is modeled as a super-Gaussian filter of order eight [8] and bandwidth $2R_b$ (R_b, bit rate over code rate), while the electrical filter is modeled as a Gaussian filter of bandwidth $0.65R_b$. The transmission media considered has a dispersion map composed of SMF and DCF sections having a residual dispersion of 272 ps/nm. An Erbium-doped fiber amplifier is used after SMF-DCF sections to compensate the attenuation loss. The SMF attenuation coefficient, dispersion, dispersion slope, nonlinear refractive index and effective cross-sectional area are set to 0.21 dB/km, 17 ps nm^{-1} km^{-1}, 0.065 ps nm^{-2} km^{-1}, 2.6×10^{-20} m^2/W and 80 μm^2 respectively. Corresponding DCF parameters are 0.5 dB/km, -100 ps nm^{-1} km^{-1}, -0.33 ps nm^{-2} km^{-1}, 2.6×10^{-20} m^2/W and 30 μm^2. An average power per

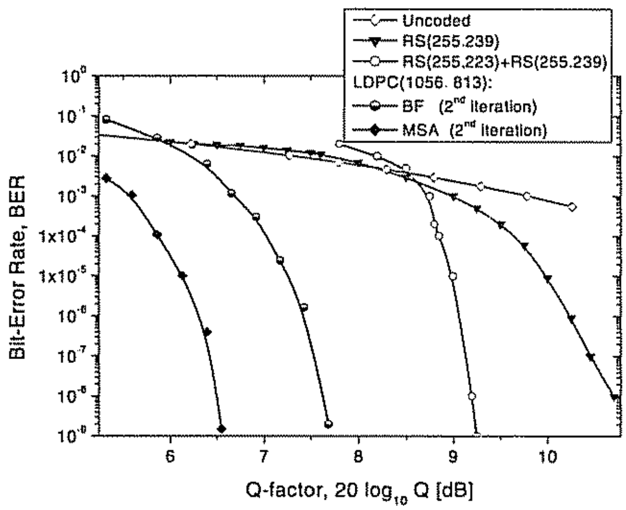

Figure 2. Bit-error-rate versus Q-factor for AG(2,2^5) based low-density parity-check (LDPC) code.

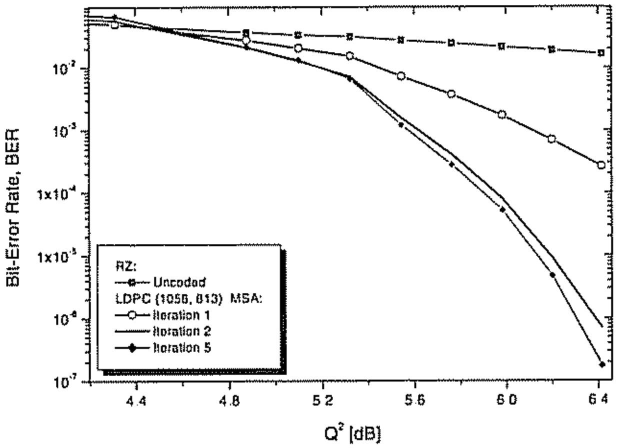

Figure 3. Bit-error-rate versus Q-factor with min-sum algorithm (MSA) in decoding for affine geometry LDPC (1056,813) for return-to-zero (RZ).

channel of 0 dBm and a NRZ signaling format are assumed.

For a BER value of 10^{-9}, the LDPC (1056,813) scheme with simple BF decoding outperforms the conventional RS(255,223) + RS(255,239) concatenation scheme by more than 1.5 dB, while the soft-decision variant based on the min-sum algorithm is better by 2.7 dB. It also outperforms the much more complex block turbo code based on a product of two BCH (128,113,6) codes (with five iterations and comparable redundancy of 28%) by 0.5 dB. (More details on RS/turbo code performance in optical communications can be found in References [3, 4].) Notice that the complexity of the RS/turbo decoder is much higher than that of a LDPC decoder of equal or comparable length. Another important observation is that coding gain at lower BER (not shown in the figure) will be larger because of the steeper waterfall curve of LDPC codes [11].

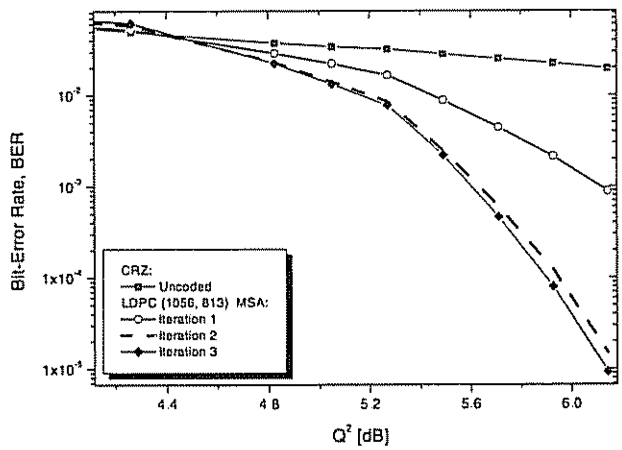

Figure 4. Bit-error-rate versus Q-factor with MSA in decoding for affine geometry LDPC (1056,813) for CRZ format.

For RZ signal format, Figure 3 and CRZ signal, Figure 4, the coding gains comparable with NRZ format are found.

6. CONCLUSION

A novel error control scheme for long haul optical communication systems based on LDPC codes and iterative decoding is presented in this paper. The LDPC code is constructed using affine geometries. The BF decoding algorithm and iterative decoding based on min-sum algorithm are applied. In just a few iterations, 1.5–2.7 dB improvement over RS(255,223) + RS(255,239) concatenation scheme, that is 3–4 dB over RS(255, 239), code is found. The proposed code outperforms the turbo code based on a product of two BCH(128,113,6) codes proposed in Reference [3] by 0.5 dB.

As opposed to recent References [3, 4] where the AWGN assumption is applied, we consider the performance of affine geometry codes in the presence of ASE noise, pulse distortion due to fiber nonlinearities, residual dispersion, crosstalk effects, ISI etc.

Different modulation formats, NRZ, RZ and CRZ, were considered and comparable coding gains were found.

REFERENCES

1. Vareille G. Julien B, Pitel F, Marcerou JF. 3.65 Tb/s (365 × 11.6 Gb/s) transmission experiment over 6850 km using 22.2 GHz channel spacing in NRZ format. In *Proceedings of 27th European Conference on Optical Communications*, 2001, Vol. 6. pp. 14–15.
2. Grover WD. Forward error correction in dispersion-limited lightwave systems. *Journal of Lightwave Technology* 1988; 5–6:643–654.
3. Sab OA. FEC techniques in submarine transmission systems. *Proceedings of Optical Fiber Communication Conference*. 2001; 2:TuF1-1–TuF1-3.
4. Sab OA, Lemarie V. Block turbo code performances for long-haul DWDM optical transmission systems. *Proceedings of Optical Fiber Communication Conference*, 2001; 3:280–282.
5. Berrou C, Glavieux A. Near optimum error-correcting coding and decoding: turbo codes. *IEEE Transactions on Communications* 1996; 44:1261–1271.
6. Kou Y. Lin S, Fossorier MPC. Low-density parity-check codes based on finite geometries: a rediscovery and new results. *IEEE Transactions on Information Theory* 2001; 47(7):2711–2736.
7. Agrawal GP. *Nonlinear Fiber Optics*. Academic Press: San Diego, CA. 1995.
8. Djordjevic IB, Vasic B. An advanced direct detection receiver model. *Journal of Optical Communications* 2004; 25(1):6–9

9 Gallager RG. *Low Density Parity Check Codes* MIT Press: Cambridge. MA, 1963.
10 Vasic B Structured iteratively decodable codes based on Steiner systems and their application in magnetic recording In *Proceedings of Globecom*, Vol 5, San Antonio. USA, 2001, pp 2954–2960
11 Vasic B Combinatorial constructions of low-density parity check codes for iterative decoding *IEEE Transactions on Information Theory* 2004; **50**: 1156–1176.
12 Hagenauer J. Offer E. Papke L. Iterative decoding of binary block and convolutional codes *IEEE Transactions on Information Theory* 1996; **42**(2):439–446.
13 Fossorier M, Mihaljevic M, Imai H Reduced complexity iterative decoding of low-density parity-check codes based on belief propagation *IEEE Transactions on Communications* 1999; **COM-47**: 673–680.
14 Chen J, Fossorier M Near optimum universal belief propagation based decoding of low-density parity-check codes *IEEE Transactions on Communications* 2002; **COM-50**:406–414.
15 Golovchenko EA. Pilipetskii AN, Bergano NS, Davidson CR, Khatri FI, Kimball RM, Mazurczyk VJ Modeling of transoceanic fiber-optic WDM communication systems *IEEE Journal on Selected Topics in Quantum Electronics* 2000; **6**(2):337–347

APPENDIX A: MIN-SUM DECODING ALGORITHM

For any codeword $x = (x_v)_{1 \leqslant v \leqslant n}$ in a linear block code given by the parity-check matrix H, the following set of equations is satisfied

$$\sum_v h_{c,v} x_v = 0, \quad 1 \leqslant c \leqslant n-k \tag{A1}$$

The above equations are called parity-check equations. Iterative decoding can be visualized as message passing on a bipartite graph representation, called Tanner graph, of the parity check matrix [11, 12]. There are two types of vertices in the graph: check vertices (check nodes) indexed by c and variable vertices (bit nodes) indexed by v. An edge connecting vertices c and v exists if $h_{c,v} = 1$, i.e. if variable v participates in the parity-check equation c, For example, the bipartite graph corresponding to

$$H = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 \end{bmatrix}$$

is shown in Figure A1.

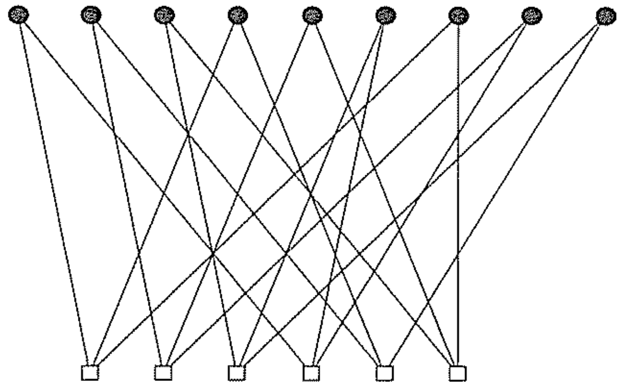

Figure A1 An example of a bipartite graph

Decoding can be done as follows. First, *a priori* information of the bit at position v, $\mu_v^{(0)}$, is taken as the channel sample and messages passed from node v to node c in the bipartite graph, $\lambda_{v,c}^{(0)}$, are initialized to $\mu_v^{(0)}$. In jth iteration, we update the messages to be passed from check node c to bit node v, $\Lambda_{c,v}^{(j)}$, as

$$\Lambda_{c,v}^{(j)} = \prod_{w \neq v} \operatorname{sign}\left(\lambda_{w,c}^{(j-1)}\right) \times \min_{w \neq v} \left|\lambda_{w,c}^{(j-1)}\right| \tag{A2}$$

and messages to be passed from bit node v to check node c, $\lambda_{v,c}^{(j)}$, according to

$$\lambda_{v,c}^{(j)} = \mu_v^{(0)} + \sum_{d \neq c} \Lambda_{d,v}^{(j)} \tag{A3}$$

The last step in iteration j is to compute updated normalized log-likelihood ratios $\mu_v^{(j)}$ according to

$$\mu_v^{(j)} = \mu_v^{(0)} + \sum_c \Lambda_{c,v}^{(j)} \tag{A4}$$

For each bit x_v the estimation is made according to

$$\hat{x}_v = \begin{cases} 1, & \text{if } \mu_v^{(j)} < 0 \\ 0, & \text{otherwise} \end{cases} \tag{A5}$$

Decoding halts when a valid codeword $\left(\sum_v h_{c,v} \hat{x}_v = 0\right)$ or a maximum number of iteration has been reached. The steps (A2) and (A3) can be viewed as propagation of 'beliefs' in a code bipartite graph [11–14].

AUTHORS' BIOGRAPHIES

Ivan B. Djordjevic received his Dipl. Ing., M.Sc. degrees and Ph.D., all in electrical engineering, from the University of Nis, Serbia. From 1994 to 1996, he was with the University of Nis, Serbia. From 1996 to 2000, he was with the State Telecommunications Company (Serbia Telecom), District Office for Networks-Nis, Serbia. He was involved in digital transmission systems commissioning and acceptance, design, maintenance, installation and connection. From 2000 to 2001, he was with the National Technical University of Athens, Greece; and with TyCom US Inc. (now TyCo Telecommunications), U.S.A. He was involved in modeling and simulation of DWMD systems. During 2002 and 2003, he was with the University of Arizona, Tucson, U.S.A.; University of Bristol, U.K. and University of the West of England, Bristol, U.K.; working on forward error correction and iterative decoding for optical transmission, optical CDMA, high-speed transmission and optical switches. He is now with the University of Arizona, Tucson, U.S.A.; on leave from University of the West of England, Bristol, U.K. Dr. Djordjevic is the author of more than 35 international journal articles and more than 45 international conference papers. His research interests include DWDM fiber-optic communication systems and networks, FEC for optical communications, optical CDMA, optical packet switching, coding theory, coherent optical communications and statistical communication theory.

Bane Vasic received his B.Sc., M.Sc. degrees and Ph.D., all in electrical engineering, from the University of Nis, Serbia. From 1996 to 1997, he worked as a visiting scientist at the Rochester Institute of Technology and Kodak Research, Rochester, NY, where he was involved in research in optical storage channels. From 1998 to 2000, he was with Lucent Technologies, Bell Laboratories. He was involved in research coding schemes and architectures for high-speed applications. He was involved in research in iterative decoding and low-density parity check codes, as well as development of codes and detectors implemented in Lucent (now Agere) chips. Presently, Dr. Vasic is a Faculty Member of the University of Arizona, Electrical and Computer Engineering Department. He has authored more than 25 journal articles, more than 50 conference articles, more than half a dozen book chapters and one book. He is a member of the editorial board of the IEEE Transactions on Magnetics. He served as a technical program chair, IEEE Communication Theory Workshop, 2003, and as co-organizer of the Center for Discrete Mathematics and Theoretical Computer Science (DIMACS) Workshops on Optical/Magnetic Recording and Optical Transmission and Theoretical Advances in Information Recording, 2004. His research interests include coding theory, information theory, communication theory and digital communications and recording