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Signal formats and error correction in optical transmission

Formats de signal et correction d'erreur dans les transmissions optiques

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Abstract

We review the advantages and drawbacks of the main optical modulation formats, comparing the standard intensity-modulated ones to more sophisticated phase and intensity modulated formats for high capacity or long distance transmission. Furthermore, different Forward Error Correction solutions, from standard Reed Solomon (RS) to block turbo codes, are presented and their impact on optical transmission system design is discussed. ***To cite this article: O. Ait Sab, H. Bissessur, C. R. Physique 4 (2003).***

Résumé

Nous présentons ici les avantages et les inconvénients des principaux formats de modulation optique. Pour accroître la capacité et/ou la distance de transmission, les modulations habituelles en intensité cèdent progressivement la place à des formats plus complexes, modulés à la fois en intensité et en phase. De plus, différents types de codage correcteur d'erreurs appliqués aux systèmes de transmission optique sont décrits et leurs performances comparées. ***Pour citer cet article : O. Ait Sab, H. Bissessur, C. R. Physique 4 (2003).***

Keywords: Modulation formats; Phase modulation; Duobinary; FEC; RS codes; BCH code; Concatenated codes; Turbo codes; Optical fiber transmission systems

Mots-clés : Formats de modulation ; Modulation de phase ; Duobinaire ; Code correcteur d'erreurs ; Codes RS ; Codes BCH ; Codes concaténés ; Turbo codes ; Transmission optique

1. Introduction

Over the past ten years, massive capacity increase has been achieved in optical systems with the technique of *wavelength-division-multiplexing* (WDM), where several wavelengths, each modulated at 10 to 40 Gb/s, are multiplexed into one optical fibre. The main effects limiting transmission performance are accumulated amplifier noise, crosstalk between channels, chromatic dispersion, and non-linear effects, which usually interact together. For example, the *optical signal-to-noise ratio*

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(OSNR) can be improved by increasing signal power, but the non-linear effects tend to limit the maximum power that can be launched. The latter also cause spectral broadening and increase the crosstalk between channels.

The optical electric field can be modulated either in *intensity* or in *phase*. However, the most common detection scheme uses a photodiode and therefore measures only the light's intensity. *Coherent detection* (i.e., beating with a local source before the photodiode) can detect the light's phase, but is more difficult to realize and has not, so far, been used in deployed systems.

Modulation formats and *forward error correction* (FEC) are keys to optimal transmission. The adequate format can be chosen so as to be more resistant to noise, to chromatic dispersion, or to non-linear effects, or to reduce crosstalk between channels. Until now, one modulation format has not proved superior for all applications, and the final choice will be determined by a trade-off between crosstalk, resistance to noise and nonlinearity, depending on the transmission link. Thus, working at 40 Gb/s with 50 GHz channel spacing will enhance the linear crosstalk aspect, whereas long distance transmission will emphasize the resistance to nonlinearity.

FEC (channel coding) provides significant margin that can increase transmission distance, amplifier spacing and/or system capacity. Indeed, most modern optical fiber transmission systems use the standard *Reed Solomon* RS(255,239) code. It was introduced first in submarine transmission systems in the early 1990s [1]. During the last decade, FEC development for optical transmission was made by submarine transmission system suppliers [2–4]. The explosion in demand of transmission capacity and the need to reduce costs in long-haul and ultra long-haul transmission systems are now driving to the use of more powerful FEC codes in both submarine and terrestrial systems. Moreover, the recent progress in microelectronics device technology has opened the way for the implementation of more powerful and complex FEC schemes.

The first part of this paper describes the various modulation formats used in installed optical systems and alternative formats for reaching higher capacity or longer distance. The second part is related to FEC coding schemes. First and second generation FEC deployed in optical transmission systems are described as well as future solutions.

2. Modulation formats

2.1. Standard modulation formats: Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ)

The simplest digital optical modulation formats, which are actually used in installed systems, rely on intensity modulation of the light (see Fig. 1). NRZ is easy to generate and requires only NRZ-type electrical data. Its spectral width allows channel spacing down to $2.5 \times$ bit-rate. RZ requires two optical modulators, one for data coding and one for pulse generation, making its implementation more complex. Whereas its spectral width is larger than NRZ's, allowing channel separation down to 3–4 $\times$ bit-rate only (depending on the pulse width), its remarkable properties versus non-linear transmission effects enable higher power

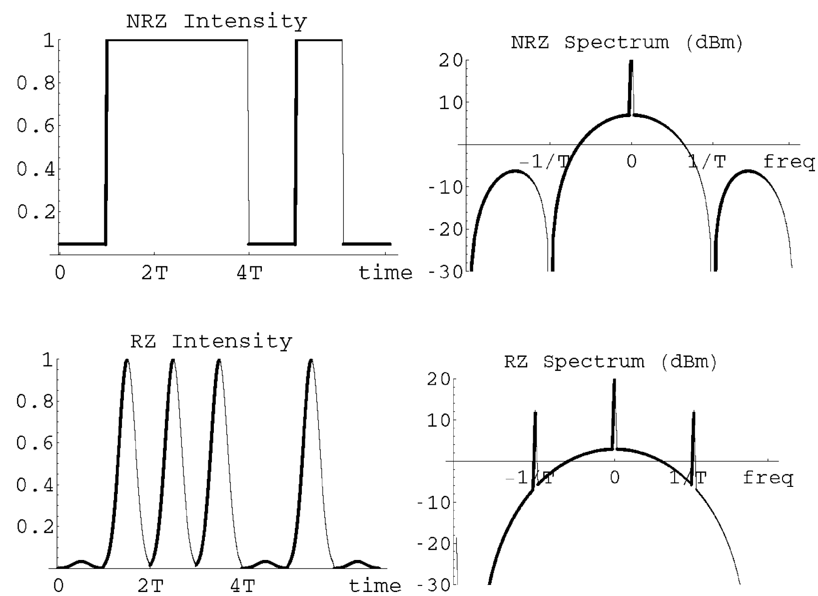

Fig. 1. Comparison between NRZ (top) and RZ (bottom) formats; left curves: time-variation of the optical intensity for a sequence of 0111010; right curves: intensity spectrum (vertical scale in dB). T is the bit-time.

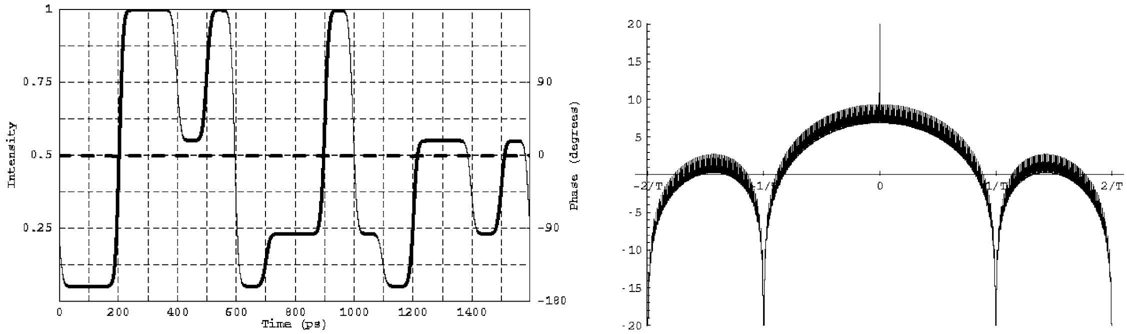

Fig. 2. Four level intensity coding. Left figure: time-variation of the intensity (straight line) and the phase (dotted line). The right graph shows the optical spectrum in dB. Here, T is the symbol time; the bit-time is therefore $T/2$.

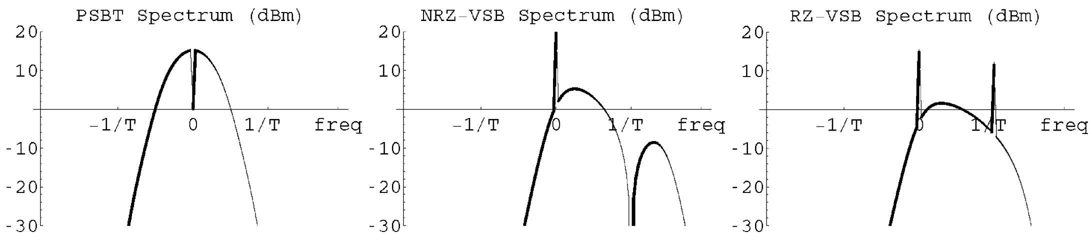

Fig. 3. Optical spectra of PSBT (left), NRZ-VSB (middle) and RZ-VSB (right) signals. T is the bit-time. The vertical scale is expressed in dB.

launched into the fiber. In principle, the RZ pulse can be designed so that the dispersion effect is exactly compensated by the (single-channel) non-linear effects, thus giving rise to so-called *solitons* [5]. However, when amplifier noise and non-linear WDM interactions are taken into account, optimisation of the soliton results in a format similar to standard chirped RZ described below. Submarine systems have relied on the RZ format. Very long distances have been spanned in single-channel experiments (35 000 km at 10 Gb/s in a laboratory experiment). However, when WDM was introduced, it was found that the spectral width of standard RZ did not allow narrow channel spacing: modulation at 10 Gb/s with 25 GHz channel spacing gives better results with the NRZ format [6]. Tolerance to chromatic dispersion can also be an issue, RZ being more sensitive to chromatic dispersion than NRZ. Adding some phase variation (chirp) to the RZ signal improves the tolerance to non-linear effects over submarine distances [7]; this is the chirped RZ format, whose bandwidth, however, is even wider than that of RZ.

2.2. High spectral efficiency

Transmission with densely spaced channels (e.g., 50 GHz spacing at 40 Gb/s or 12.5 GHz spacing at 10 Gb/s) is often considered as a key technology for the next generation WDM systems. Several formats have so far been investigated for minimal bandwidth occupation, such as *multilevel*, *duo-binary* or *vestigial side-band* binary formats.

2.2.1. Multi-level formats

Multi-level M-ary coding consists in grouping the bits and coding them on M intensity or phase levels. For the same transmitted information, the spectral bandwidth is then reduced by $\log_2(M)$, but the associated sensitivity penalty is high: 3.3 dB penalty is estimated for $M = 4$ intensity levels, the experimental results lying around 8 dB. Moreover, the complexity of the receiver is increased, since it has to discriminate between M intensity levels [8]. Recently, $M = 4$ phase coding (and intensity detection) has shown good results [9]: the phase modulation is transformed into two intensity-modulated signals, one discriminating the $(0, \pi)$ phases and the other the $(-\pi/2, \pi/2)$ phases. As a result, two binary receivers can be used, with good sensitivity properties.

2.2.2. Binary formats

Binary formats greatly simplify the receiver, which operates with only one decision threshold. Narrow spectral occupation can be achieved with the *duobinary* or *phase-shaped binary transmission* (PSBT) format, which relies on 3 level coding [10,11]. Usually, 0, $+1$ and -1 levels are chosen, which allows for a standard intensity receiver, which detects only the 1 and 0 levels. The PSBT format reduces the optical and electrical bandwidth by a factor of 2 versus NRZ, but needs an electrical pre-coder. It induces a sensitivity penalty of typically 4 dB versus NRZ, which can be reduced by re-modulating with an NRZ signal [12]. Dense WDM transmission with channels modulated at 40 Gb/s separated by 50 GHz has been shown [13] using this format. One of the attractive features of PSBT, especially at 40 Gb/s, is its tolerance to chromatic dispersion.

In NRZ or RZ modulation, the information on both sides of the carrier is actually redundant. Therefore, using only one of the side-bands should provide a signal with the same quality, while reducing the optical bandwidth by a factor of (almost) two. This so-called *vestigial side-band* (VSB) signal can be obtained either by optically filtering the signal, or by using a Hilbert transform in the electrical domain. An interesting application is shown in [14], where VSB is used only at the receiver, with an alternate spacing of 50/75 GHz at a bit-rate of 40 Gb/s. Other applications use VSB at both the transmitter and receiver sides, demonstrating 0.8 bit/s/Hz information spectral density at 40 Gb/s using NRZ-VSB [15], and in [16], a density of 0.53 bit/s/Hz using RZ-VSB at 10 Gb/s over 9200 km. In all these cases, the quality of the resulting VSB format depends critically on the characteristics of the optical filter.

Another approach involves spectral narrowing by symmetric optical filtering around the carrier at the transmitter end, while multiplexing the different channels on the fiber: this method has been used with the RZ format [17], the *carrier-suppressed* RZ (CS-RZ) format [18] or the PSBT format [19]. In general, this strong signal filtering degrades the intrinsic signal quality, but reduces the crosstalk from adjacent channels. In the case of PSBT, however, the signal already has a narrow bandwidth and small crosstalk, and filtering actually even slightly increases the signal quality.

2.3. Long-distance transmission

Other modulation formats have been developed for long-haul transmission (typically several thousands of km), where the main issue is non-linear effects. These formats are based on the RZ format, whose pulses are already more tolerant to non-linear effects and to OSNR. Usually, some phase modulation is added in order to reduce its bandwidth and allow for closer channel spacing.

2.3.1. Carrier-suppressed RZ

The first RZ-derived format is carrier-suppressed RZ (CS-RZ): the information is coded on the pulse intensity and the phase alternates systematically between 0 and π from pulse to pulse (see Fig. 4). Therefore, the time-averaged field is zero, and the spectrum shows no carrier – hence its name. The CS-RZ format has a narrower spectrum than RZ (see Fig. 4), with two sub-carriers appearing on both sides of the carrier. Detection requires a typical RZ receiver. It has been shown that CS-RZ has a larger tolerance than RZ with respect to non-linear effects and chromatic dispersion [20]. Since its spectral width is comparable to that of NRZ, 40 Gb/s transmission with 100 GHz spacing (i.e., at 2.5 × bit-rate) is also possible [21]. Recently, the first experiment over transpacific distance at 40 Gb/s was demonstrated using this format and a specially designed fiber line [22].

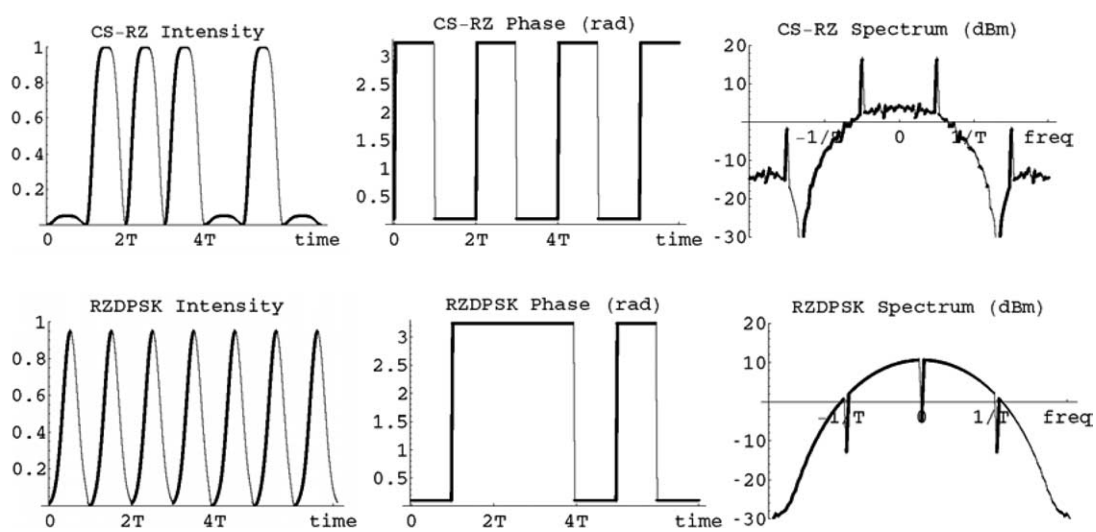

Fig. 4. Comparison between CS-RZ and RZ-DPSK. Left curves: time-variation of the optical intensity for a sequence of 0111010; middle curves: time-variation of the optical phase for a sequence of 0111010; right curves: optical spectrum.

2.3.2. Phase-Shift Keying (PSK)

Pure phase modulation with constant intensity has been suggested in order to increase the non-linear tolerance of the signal: since the non-linear Kerr effects depend only on the light's intensity, the non-linear phase shift should be the same on the '0's and '1's. In order to use intensity detection, the phase modulation has to be converted to intensity modulation with a Mach–Zehnder filter or a bandpass filter placed before the receiver [23].

Recently, RZ-DPSK (differential PSK) has been introduced: like CS-RZ, it combines phase modulation with RZ-type intensity pulses, but in this case the information is coded on the phase modulation, and the pulses are identical for the '1's and the '0's (see Fig. 4). This format was shown to reduce intra-channel non-linear effects (i.e., interactions between pulses of the same channel) [24], thus improving the non-linear tolerance compared to standard RZ, while keeping the resistance to optical noise. Thanks to all these characteristics, 5200 km were spanned with channels at 40 Gb/s spaced by 100 GHz [25].

2.4. Conclusion

Various modulation formats have been developed in order to reduce transmission impairments over different kinds of fiber links; the most widely used are NRZ in terrestrial systems, because it is simple to generate, and RZ in submarine systems, because it tolerates large input power. High information density can be obtained by using multi-level or bandwidth-reduced formats like PSBT or VSB. Long distance transmission with closer channel spacing is possible with the more recent CS-RZ or RZ-DPSK formats.

3. Forward error correction

3.1. Introduction

The principle of FEC is relatively simple to understand [26]. The FEC encoder introduces, in a controlled manner, some redundancy in the binary information sequence that can be used at the receiver to check and correct (if possible) transmission errors. More precisely, the encoder transforms a sequence of k information symbols into a unique n-symbol sequence, called a *code word*. The ratio k/n is called the *code rate*. It gives a measure of the redundancy introduced by the encoding process. Two major types of decoding: hard and soft decision decoding can be used to recover the information bits at the receiver side. In hard decoding strategy, received samples are compared first at the output of the demodulator to the optimal threshold; hard decisions are taken and fed to the decoder where the errors are corrected. In the case of soft decoding strategy, the receiver does not take any decision; the received samples are quantized in q-bit word and then are fed to FEC decoder. The decoder would make use of the information coming from the channel in order to perform better decoding than in hard decoding case.

The effectiveness of a particular FEC code is expressed in terms of *net coding gain* (NCG), defined as the difference between the Q factor obtained without data encoding and the Q_b factor (normalized Q factor per information bit) obtained with the implementation of error correction. This net coding gain is usually given for a *bit-error rate* (BER) of 10^{-13} after correction (corresponding to a Q factor of 17.3 dB). The main constraint in optical fiber systems is the high bit rate transmission. This requires a low redundancy FEC scheme.

3.2. Standard FEC scheme: Reed–Solomon codes

The first FEC scheme introduced in optical fiber transmission systems was the $\mathrm{RS}(255, 239)$. In fact, RS codes are a good solution for high bit rates due to their non-binary structures. RS codes offer efficient error correction capability with low redundancy, as well as immunity to short bursts of errors. Moreover, the RS encoder/decoder implementation can be relatively simple. The $\mathrm{RS}(255, 239)$ has been adopted by the ITU G975 as standard FEC for undersea optical fiber transmission systems and starting also to be a standard for terrestrial optical transmission systems: ITU G709.

The main parameters of RS code are (n, k), where n stand for the code length, and k is the number of information symbols. The error-correcting capability of an RS code is equal to $(n - k)/2$.

To achieve a high bit rate transmission, a parallelism of codec (encoder or decoder) is needed. MUX and DMUX are used to divide the overall bit rate into sub-streams, each being encoded and decoded by an elementary codec. Fig. 5 shows a block chart of optical transmission system using FEC.

The $\mathrm{RS}(255, 239)$ adds about 6.7% of redundancy and corrects up to 8 erroneous symbols among 255. The net coding gain obtained at 10^{-13} BER after correction is about 5.8 dB (Fig. 7). However, this coding gain becomes insufficient for the new generation of optical transmission systems using 10 Gb/s dense-WDM (DWDM) techniques which require powerful coding scheme to achieve a higher capacity transmission. Concatenated codes offer an easy and simple way to construct a powerful coding scheme with low decoding complexity. They have been widely deployed within the new generation of submarine systems [2–4]. The principle of concatenated codes is presented in the next section.

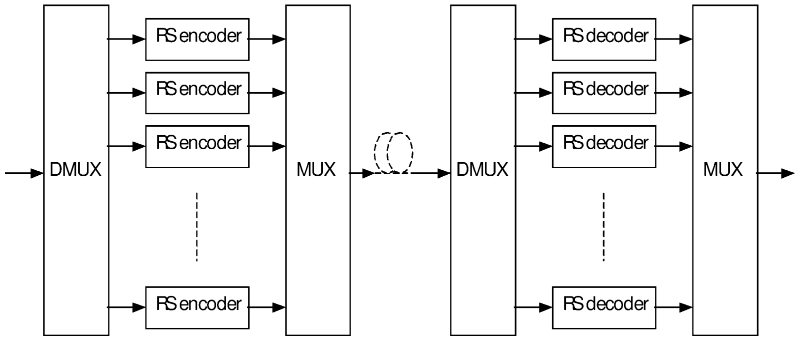

Fig. 5. Block chart of optical fiber transmission system using RS FEC.

3.3. Concatenated codes

Today, concatenated coding schemes are considered as being the best solutions for powerful protection of digital information against errors. The motivation for using concatenated coding schemes is to achieve the same performance as that of a single and powerful error correcting code but with a lower decoding complexity by associating two (ore more than two) less powerful error correcting codes for data coding. In practical applications, the number of codes used in a concatenated coding scheme is limited to two or three.

3.3.1. Concatenated code principle

Concatenated FEC codes were first proposed by Forney in 1966 [27] and can be divided into two categories. The first one consists of the serially concatenated FEC codes while the second one concerns FEC codes concatenated in parallel. Serial concatenation gives the best result in terms of coding gain for a reasonable complexity of the decoder. In this paper we have considered only serial concatenation.

Fig. 6 shows the serially concatenated coding scheme principle. In this scheme, the incoming data is encoded first by an outer encoder. Then the encoded data is interleaved before being encoded by an inner encoder and transmitted through the channel to the receiver.

At the receiver end, inner decoding is performed first, and then the decoded data is fed to the outer decoder after de-interleaving. The performance and the complexity of concatenated coding scheme depends on its elementary codes and the interleaving design.

3.3.2. Examples and performance of concatenated codes

The first concatenated codes introduced in optical fiber transmission system were based on concatenated RS codes [2–4]. Indeed, RS codes have a long history of use as part of concatenated codes in long reach applications [28] and are also applied as standard for optical submarine transmission systems. RS codes were then a logical selection as elementary codes for a concatenated coding scheme.

The performances of two concatenated RS codes have been evaluated by Monte Carlo simulation. The first uses a concatenation of $\mathrm{RS}(255,239)+\mathrm{RS}(255,239)$ having a redundancy equal to 13.8%. The second has 22% of redundancy and uses $\mathrm{RS}(255,239)+\mathrm{RS}(255,223)$. The two schemes use a serial concatenation with a 32 bytes interleaver depth. The BER curves of the two concatenated RS codes are plotted in Fig. 7.

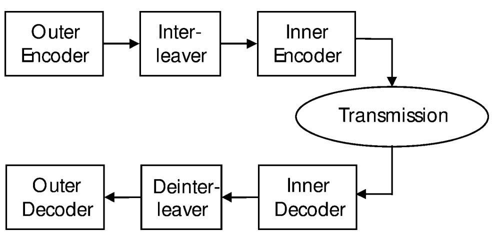

Fig. 6. Concatenated coding scheme.

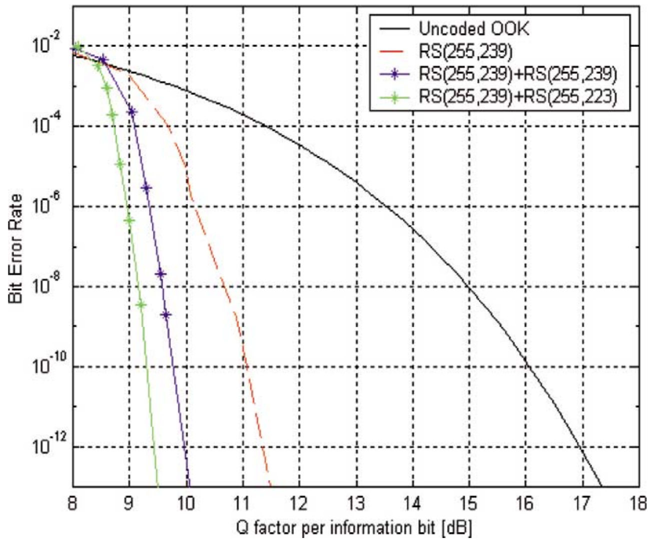

Fig. 7. BER versus Q_b factor of RS(255, 239) code, RS(255, 239) + RS(255, 239) and RS(255, 239) + RS(255, 223) concatenated codes.

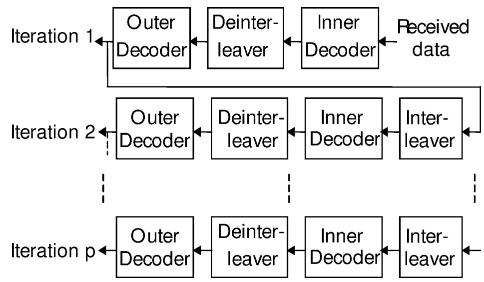

Fig. 8. Iterative decoding principle.

Compared to the single RS(255, 239), the concatenated RS(255, 239) + RS(255, 239) features 1.4 dB additional coding gain for 10^{-13} BER. With RS(255, 239) + RS(255, 223) configuration, the NCG increases by 2 dB.

3.3.3. Iterative decoding

Concatenated codes can be further decoded iteratively. This technique offers the advantage of improving FEC efficiency without a line bit rate increase since no modification of the FEC encoder is required. The received data is decoded first by the inner decoder, de-interleaved and then decoded by the outer decoder. By re-interleaving the decoded data, the interleaver data output has the same structure as the data at the input of the inner decoder. It can be reprocessed by the inner decoder and then the decoding can be iterated. We defined one iteration as the decoding by an inner decoder followed by an outer decoder. Fig. 8 shows the iterative decoding principle while Fig. 9 depicts the performance of concatenated RS(247, 239) + RS(255, 247) using iterative decoding.

Concatenated RS(247, 239) + RS(255, 247) code adds 6.7% of redundancy. To achieve 10^{-13} BER, a Q_b factor of 11 dB is required when using 1 iteration decoding step which yields to 6.3 dB NCG. This NCG is increased respectively by 1.1 dB and 1.5 dB after 2 and 4 iterations. Compared to single RS(255, 239) which has the redundancy, 2 dB additional coding gain can reached after 4 iterations.

Recently, BCH codes (after *Bose, Chaudhuri and Hocquenghem*) started to be considered for optical transmission systems. Concatenated RS BCH codes and BCH product codes give a significant performance improvement when compared to concatenated RS codes. BCH codes are very attractive specially when associated with iterative decoding algorithm based on soft input decoding and soft output decision '*block turbo codes* (BTC)'. It has been shown that BTC achieve a performance close to their *Shannon* theoretical limit [29]. Next section is dedicated to BTC.

3.4. Block Turbo Codes (BTC)

In hard-decoding strategy, received samples are compared to the optimal threshold and hard decisions are taken. FEC hard decoding is sub-optimal because it does not take account of all the information coming from the transmission channel. In the case of soft decoding strategy, the receiver does not take any decision, the received optical samples levels are quantized in q bits word and then are fed to FEC decoder.

An example of concatenated coding scheme using soft decoding and applied to an optical submarine system is described in [30]. In this scheme, RS(255, 239) was used as outer code and rate 1/2 convolutional as inner code associated with soft-decision *Viterbi* algorithm. This scheme demonstrated a 10 dB net coding-gain margin. However, this solution generates high redundancy (>100%), thus leading to a prohibitive implementation at a very high bit rate.

Recently, a new generation of codes called 'block turbo codes' was invented [29]. They are based on a concatenation of two or more block codes associated with an iterative decoding based on soft input and soft output decoding. We present here the performance of BTC BCH$(128, 113, 6)^2$ for submarine transmission systems. This solution has 28% of redundancy. We

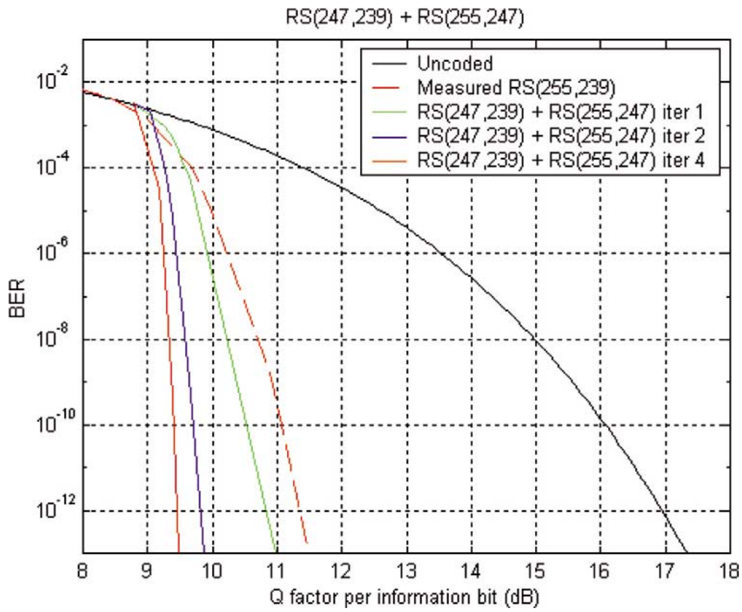

Fig. 9. BER versus Q_b factor of RS(255, 239) and concatenated RS(247, 239) + RS(255, 239) after 1, 2 and 4 iterations.

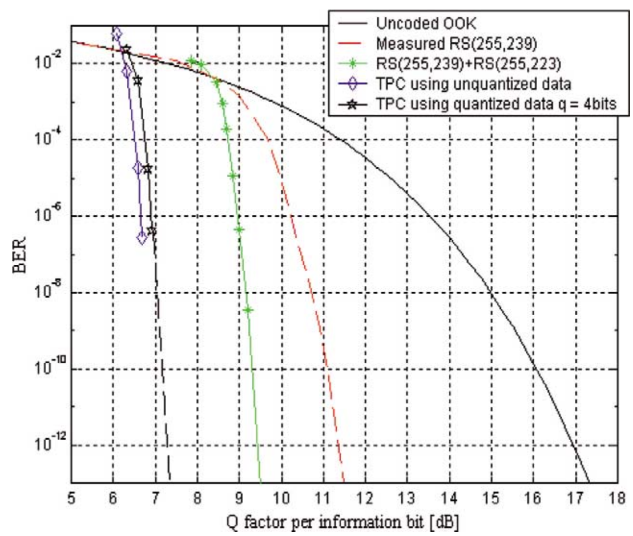

Fig. 10. BTC BCH$(128, 113, 6)^2$ performance for optical transmission.

plotted first in Fig. 10, the optimal performance of BTC BCH$(128, 113, 6)^2$ using unquantized data and then the performances of simplified algorithm using quantized data and hardware configuration [31]. The BER curves are obtained after 5 iterations. These performances are compared to the previous solutions using RS codes.

At BER of 10^{-6}, the coding gain degradation is only 0.35 dB when using 4 quantization bits compared to optimal algorithm performance. By extrapolating the BER curves to 10^{-13}, we obtain about 10 dB net coding gain margin compared to an uncoded transmission. Fig. 10 gives also a comparison with existing RS(255, 239) and the concatenated RS(255, 239) + RS(255, 223) presented previously. The BTC BCH$(128, 113, 6)^2$ gives respectively 2 dB and 4 dB additional coding gain margin compared to concatenated RS codes and existing RS(255, 239). Hereafter we present the NCG margin impact in submarine transmission systems.

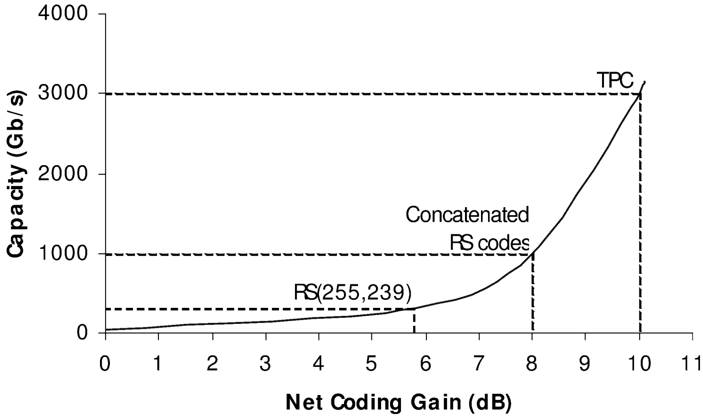

Fig. 11. Transmission capacity versus the FEC net coding gain.

3.5. Impact of FEC net coding gain in submarine transmission systems

Submarine transmission system design is based on two parameters, transmission length and capacity (number of wavelengths at given channel bit rate). The system has to be *transmission error-free* at the end of its life (typically BER $< 10^{-13}$ after 25 years). Thus requires a minimum Q factor called Q-limit. Increasing the transmission distance for an optically amplified system leads to an increase of the number of the in-line amplifiers and a degradation of received Q factor. Indeed, the major degradation, induced by an optically amplified fiber transmission system, is the accumulated spontaneous emission noise added by each amplifier.

Submarine transmission systems use erbium amplifiers with a limited bandwidth. A large capacity transmission leads to a high number of wavelengths at lower channel spacing. Packing the wavelength close together increases the non-linear effects and thus degrades the received Q factor.

As previously showed, FEC techniques bring some coding gain margin which can be used to compensate for those kinds of degradation.

In order to assess the impact of the net coding gain on the transmission capacity, Fig. 11 plots reported experiments carried out over more than 6000 km exhibiting about 2.5 dB above the Q factor limit.

3.6. Conclusion

Forward error correction is now recognized as a key technology for DWDM systems. In this paper, different FEC scheme solutions for optical transmission systems have been presented. RS(255, 239) is the standard FEC code which adds 6.7% redundancy and yields about 5.8 dB NCG. The second FEC generation is based on concatenated RS codes which demonstrate up to 2 dB additional coding gain compared to RS(255, 239) code. Concatenated RS codes have been widely deployed and contribute to break the transatlantic terabit transmission barrier. BCH product codes and block turbo codes are very attractive for future solutions. We presented an example using BCH BTC which shows that 10 dB NCG is achievable.

References

[1] J.L. Pamart, E. Lefranc, S. Morin, G. Balland, Y.C. Chen, T.M. Kissell, J.L. Miller, Electron. Lett. 30 (4) (1994).
[2] O. Ait Sab, J. Fang, in: Proc. European Conference on Optical Communications, ECOC '99, Nice, 1999, Paper ThC2.4.
[3] C.R. Davidson, C.J. Chen, M. Nissov, A. Pilipetskii, N. Ramanujam, H.D. Kidorf, B. Pedersen, M.A. Mills, C. Lin, M.I. Hayee, J.X. Cai, A.B. Puc, P.C. Corbett, R. Menges, H. Li, A. Elyamani, C. Rivers, N.S. Bergano, in: Proc. Conference on Optical Fiber Communications, OFC '2000, Optical Society of America, 2000, Paper PD25-1.
[4] T. Mizuochi, K. Kubo, in: Proc. Suboptic '2001 Conference, Kyoto, Japan, 2000, pp. 484–487, Paper P4.2.3.
[5] A. Hasegawa, IEEE J. Selected Topics Quantum Electron. (2000) 1161–1172.
[6] G. Vareille, F. Pitel, in: Proc. Conference on Optical Fiber Communications, OFC '2001, Optical Society of America, 2001, Paper PD 22.
[7] J.B. Leroy, P. Marmier, G. Vareille, B. Julien, in: Proc. European Conference on Optical Communications, ECOC '2002, 2002, Paper 9.1.5.
[8] S. Walklin, J. Conradi, IEEE J. Lightwave Technol. (1999) 2235–2248.
[9] R.A. Griffin, A.C. Carter, in: Proc. Conference on Optical Fiber Communications OFC '2002, Optical Society of America, 2002, pp. 367–368, Paper WX6.

[10] T. Ono, Y. Yano, K. Fukuchi, T. Ito, H. Yamazaki, M. Yamaguchi, K. Emura, IEEE J. Lightwave Technol. (1998) 788–797.
[11] D. Penninckx, et al., in: Proc. European Conference on Optical Communications, ECOC '98, Madrid, Spain, 1998, pp. 537–538.
[12] H. Bissessur, L. Pierre, D. Penninckx, J.-P. Thiery, J.-P. Hamaide, Electron. Lett. 37 (2001) 45–46.
[13] H. Bissessur, G. Charlet, C. Simonneau, S. Borne, L. Pierre, C. De Barros, P. Tran, W. Idler, R. Dischler, in: Proc. European Conference on Optical Communications, ECOC '2001, Paper PD.M.1.11.
[14] S. Bigo, et al., 5.12 Tb/s (128 × 40 Gb/s) WDM transmission over 3 × 100 km of Teralight fibre, in: Proc. European Conference on Optical Communications, ECOC '2000, Munich, Germany, 2000, Paper PD 1.2.
[15] G. Charlet, J.-C. Antona, P. Tran, S. Bigo, W. Idler, R. Dischler, in: Proc. Topical Meeting on Optical Amplifiers and Applications, OAA '2002, Optical Society of America, 2002, Paper PDP1.
[16] Y. Yamada, S. Nakagawa, T. Kawazawa, H. Tada, K. Goto, in: Proc. SubOptic '01 Conference, 2001, Paper PDP 1.
[17] T. Miyakawa, I. Morita, K. Tanaka, H. Sakata, N. Edagawa, in: Proc. Conference on Optical Fiber Communications, OFC '2001, Optical Society of America, 2001, Paper PD 26.
[18] D. Grosz, A. Agarwal, S. Banerjee, A. Küng, D. Maywar, A. Gurevich, T. Wood, C. Lima, B. Faer, J. Black, C. Hwu, in: Proc. European Conference on Optical Communications, ECOC 2002, Paper PD4.3.
[19] G. Charlet, J.-P. Hamaide, S. Bigo, Y. Frignac, M. Molina, F. Beaumont, A. Klekamp, C. Simonneau, L. Pierre, W. Idler, M. Gorlier, S. Borne, J.-C. Antona, S. Lanne, P. Tran, in: Proc. European Conference on Optical Communications, ECOC '2002, 2002, Paper PD. 4.1.
[20] Y. Miyamoto, A. Hirano, K. Yonenaga, A. Sano, H. Toba, K. Murata, O. Mitomi, Electron. Lett. (1999) 2041–2042.
[21] Y. Zhu, W. Lee, C. Scahill, C. Fludger, D. Watley, M. Jones, J. Homan, B. Shaw, A. Hadjiofotiou, in: Proc. European Conference on Optical Communications, ECOC '2000, Paper PD 1.4.
[22] H. Sugahara, M. Morisaki, T. Ito, K. Fukuchi, T. Ono, in: Proc. Topical Meeting on Optical Amplifiers and Applications, OAA '2002, Optical Society of America, 2002, Paper PDP-3.
[23] H. Bissessur, G. Charlet, E. Gohin, C. Simonneau, L. Pierre, W. Idler, in: Proc. European Conference on Optical Communications, ECOC '2002, Paper 8.1.2.
[24] V.S. Grigoryan, P.S. Cho, I. Shpantzer, in: Proc. European Conference on Optical Communications, ECOC '2002, Paper P 3.29.
[25] B. Zhu, et al., in: Proc. European Conference on Optical Communications, ECOC '2002, Paper PD 4.2.
[26] S. Lin, D.J. Costello, Error Control Coding: Fundamentals and Applications, Prentice-Hall, Englewood Cliffs, NJ.
[27] G.D. Forney, Concatenated Codes, MIT Press, Cambridge, MA, 1966.
[28] R.J. McEliece, et al., JPL (Jet Propulsion Laboratory), Technical Report 94-0881.
[29] R. Pyndiah, A. Glavieux, A. Picart, S. Jacq, in: Proc. of Globecom '94 Conference, Vol. 1/3, 1994, pp. 339–343.
[30] A. Puc, F. Kerfoot, A. Simons, D.L. Wilson, in: Proc. Conference on Optical Fiber Communications, OFC '99, Vol. 4, Optical Society of America, 1999, Paper ThQ6.
[31] O. Ait Sab, V. Lemaire, in: Proc. Conference on Optical Fiber Communications, OFC '2000, Baltimore, USA, 2000, Optical Society of America, 2000, Paper ThS5-1.