Employing Concatenated-FEC to Mitigate Polarization-Sensitivity in All-optical Wavelength-Conversion

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***Abstract*—Wavelength-conversion is an essential block in building all-optical networks. Currently, all-optical wavelength-conversion can quite efficiently be performed by means of SOA. In this approach however, a significant shortcoming is the high sensitivity of error-performance to the relative polarization of optical-signals, which imposes rigid tuning requirements. To make conversion insensitive to random fluctuations of polarization, we employ a standard outband-FEC method, in combination with a novel inband-FEC method. The latter, called "FOCUS", is best suited for combating burst-form errors. This particular property of "FOCUS" matches the error-distribution generated by the associated outband-FEC code, when the two are combined in serial-concatenation. We demonstrate the corrective-power of this FEC-concatenation scheme in protecting a 10Gb/s lightwave-channel, which undergoes wavelength-conversion by means of an all-optical, SOA-based Mach-Zehnder Interferometer (MZI) switch. In this experiment, the MZI switch was purposely misadjusted, in order to increase the polarization sensitivity. We show error-free 10Gb/s wavelength-conversion and no need for polarization-control before the converter.**

I. INTRODUCTION

The information avenues, optical networking has offered, were hardly imaginable a few decades earlier. However, bandwidth-greedy applications proliferate rapidly, indicating that current status is far from future-proof. Notably, only a small fraction of the potentially available fiber-bandwidth is currently exploited. This is mainly attributable to the lack of cost-effective network elements. To alleviate this, all-optical switching emerges as a solution, viable in the long term, completely eliminating costly optoelectronic conversions [1].

A number of highly impressive laboratory experiments [2] [3] have indicated that transparent, all-optical networks are possible. To date, however, performance of key all-optical devices tends to critically rely on the precise adjustment of parameters, as for instance optical power and the randomly fluctuating polarization-state of signals. As a result, all-optical networks are limited to tightly-controlled environments; to render them field-deployable a form of Forward Error Correction (FEC) coding can be introduced, providing the necessary system margin. Implementation of FEC-coding by means of electronic devices is an established technology, which can be efficiently applied only at the end-nodes of communication channels, this way avoiding the necessity for all intermediate optoelectronic conversions.

To the best of the authors' knowledge, commercially deployed FEC systems fall almost exclusively into the "outband" category. Outband FEC methods can yield very high coding-gains, because of the involvement of an arbitrarily large amount of parity-information. For instance, 3rd generation outband FEC systems, currently deployed or considered for deployment, typically contribute a Net Coding-Gain (NCG) of approx. 10 dB [4]. This is in sharp contrast with inband methods, where room for parity allocation is a rare resource and coding-gains are moderate [5] [6] [7].

In particular, "FOCUS" is an inband FEC system [8], [5]. It has been introduced in [8] and analyzed in [9]. A coding-gain above 3.5dB has been demonstrated in combating ASE-noise in long distance transmissions [6]. FOCUS applies to SDH STM-N networks in a uniform manner with respect to the TDM rate (N). It is applicable in two modes, 'strong' & 'weak'; the latter is a trade-off between performance and complexity, which is very beneficial for cost-sensitive applications, such as METRO.

Nevertheless, all FEC codes have a common property: When channel errors exceed their corrective reach, they further damage data-integrity, instead of improving it. This effect, called error-multiplication, is induced by ill-corrections and the generated errors have a pronounced tendency to appear in burst-form. Error-multiplication is normally not supposed to manifest itself in FEC-protected optical lines with sufficient system margin. Notwithstanding, the time-variant performance of all-optical building-blocks incurs a non-negligible possibility of error-multiplication occurrence. In this regard, we propose serial-concatenation of inband and outband FEC, the inband FEC scheme acting as the 2nd line of defence [10].

In this paper, we demonstrate for the first time to our knowledge, the joint power of an inband/outband concatenation-in-series FEC-scheme, as applied to an all-

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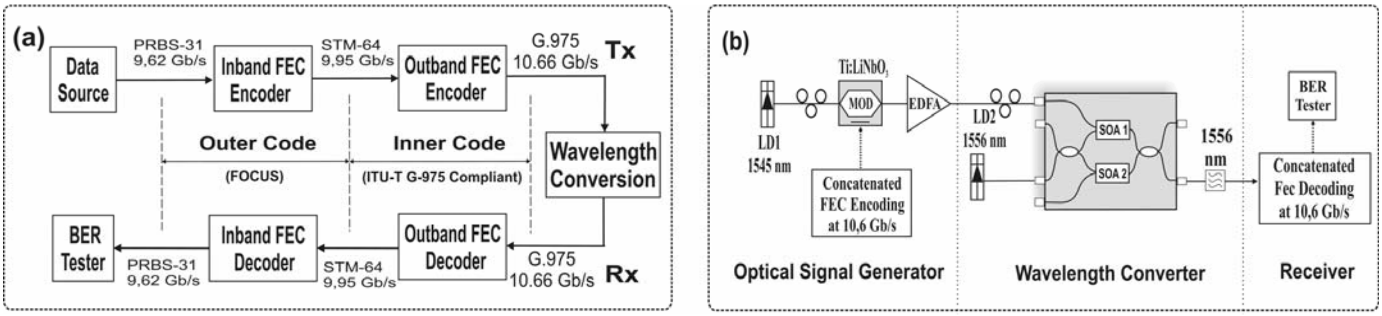

Figure 1: a) Concatenation of inband in series with outband FEC, b) Experimental setup for wavelength conversion.

optical transmission. We demonstrate that inband and outband FEC can be seamlessly integrated, taking complementary roles. Outband FEC is performed by an ITU-T G.975 (2000) recommendation compliant board (10.66Gb/s) [11]. Inband FEC (FOCUS) is implemented by means of programmable logic on 10Gb/s-capable cards. To evaluate our proposed FEC scheme, we choose wavelength-conversion, one of the enabling building-blocks for the realization of all-optical networks. The encoded data (10.66Gb/s) are fed into a wavelength-conversion device, which relies on a SOA-based Mach-Zehnder Interferometer (MZI) [12]. Post to error-correction at the receiving end, performance is constantly monitored by means of a BER-tester.

II. IMPLEMENTATION

FOCUS has been modelled in the VHDL description-language and implemented in a Xilinx® FPGA (XC2V-3000-4). One FPGA of this kind is situated on '10g-Tester', a PCB card designed for operation at data rates in excess of 10Gb/s [9]. One '10g-Tester'-card serves as the source that generates FOCUS-encoded SDH STM-64 frames, while a second one serves as the FOCUS-decoder. At the transmitting card, an Intel® LXT16717 MUX is used to serialize the SDH frames, while at the receiving card an Intel® LXT16716 DEMUX parallelizes the frames again to allow for bulk processing at lower speed. A micro-controller local to each card enables fast-Ethernet connection with a hosting PC to control the cards and collect the signal-integrity statistics from FOCUS. The most common control-functions are: FEC and scrambling activation, mode switching (weak/strong), codeword and bit error-count over the payload and interrupt request acknowledgement.

The parity-information introduced by FOCUS, occupies specific octets within the Regenerator and Multiplex-Section (RS/MS) overhead (OH) of SDH/SONET frames [8] [6]. Furthermore, the payload part of the STM-64 frames (path layer columns) is filled with a maximum-length Pseudo Random Binary Sequence (PRBS) of period 2^{31}-1, in true SDH transmission-order [6]. The above path-layer PRBS is verified at the receiving end (post to FEC), where the erroneously received bits are counted and accumulated over configurable intervals (up to 240sec), providing the BER measurement. In all BER calculations, the omission of RS/MS-OH columns from PRBS in SDH frames has been properly accounted for. Also the SDH-scrambling operation is disabled, as not to modify the properties of the underlying 2^{31}-1 PRBS pattern.

With regard to outband FEC, it is implemented by means of the Intel® IXD80102 evaluation system for the Intel® IXF30005 digital wrapper (WRAP100). The latter complies with the ITU-T recommendations G.975 (2000) and G.709 (2003), which essentially adopt the same FEC scheme i.e. 16-way byte-interleaved Reed-Solomon RS(255,239) codes [11]. In our experiment, the above outband-FEC system was operated in G.975 mode, having an exact coding-rate of 15/14. Serialization and transmission were performed by an Intel® LXT16785 MUX at 10.66Gb/s. An Intel® LXT16784 was used for reception and deserialization (10.66Gb/s).

III. EXPERIMENTAL SET-UP

Figure 1(a) above, outlines FEC-concatenation. The inband and outband FEC have been concatenated in series, the outband acting as the 'inner' code and the inband as the 'outer' code. As opposed to Forney's approach [13], no form of interleaver has been placed between 'inner' and 'outer' code, because FOCUS takes advantage of the octet-interleaving, inherent in SDH frames [8] [7].

More specifically, FOCUS-encoded frames are generated at the transmitting end, sourcing the system-side of WRAP100 at 9.95Gb/s. The line-side of WRAP100 drives an electro-optic modulator at 10.66Gb/s, feeding the wavelength-conversion setup with encoded data. At the receiving end, data entering the line-side of WRAP100, are subjected to a first round of decoding at 10.66Gb/s. Corrected STM-64 frames finally enter FOCUS-decoder at 9.95Gb/s for a second round of decoding.

Figure 1(b) above, shows the experimental setup, used for measuring the performance of the concatenated-FEC scheme. It consists of the optical signal generator and the wavelength-converter stage, comprised of a single, hybrid integrated SOA-MZI. A CW signal at 1545nm was injected into a Ti:$LiNbO_3$ electro-optic modulator, driven by the NRZ output pulses of the outband-FEC (WRAP100) transmitter. This data stream was subsequently fed into the MZI as the control-signal and wavelength-converted to 1556nm at the output of the MZI. Following the SOA-MZI, a 1 nm bandpass (BP) optical filter was used.

IV. RESULTS AND DISCUSSION

The experimental setup, described above, was used to obtain two sets of measurements. The first set led to "output-BER versus input-power" plots, which accurately characterize the proposed concatenated-FEC scheme. These curves are presented in figure 2. The second set was taken with outband-FEC on the verge of collapse, highlighting the inband-FEC protective intervention. The associated "output-BER versus input-BER" curves are given in figure 3. For optimized wavelength conversion and minimization of polarization sensitivity, the average input and control signal powers into the MZI must be 9 dBm and 6 dBm respectively. To evaluate FEC performance, the polarization sensitivity of the MZI was deliberately enhanced by reducing the signal and control powers to 1.5 dBm and 2.5 dBm respectively,

In measuring BER with respect to received-power (first set), the two extreme cases were examined: a) optimum and b) worst-case polarization of the optical control-signal, shown in figures 2(a) and 2(b) respectively. The polarization of the input wavelength to the converter was kept constant at its optimum value. Optimum- and worst-case polarizations were determined with respect to received-power, as providing the lowest- and highest-BER at the receiving end.

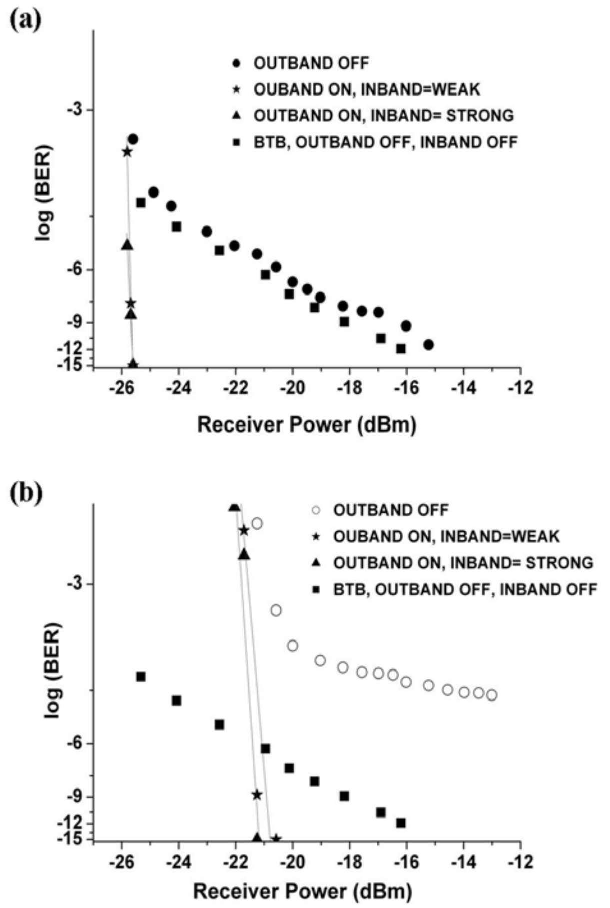

Figure 2: BER versus Received-Power curves, when control-signal polarization is a) optimal, b) worst.

At the optimum control-signal polarization, as of figure 2(a), error-free communication is achievable without FEC, when input power is at least -15dBm. FEC-activation, however, incurs a negative power-penalty of almost 10.5dB, regardless of FOCUS-mode (weak/strong), at an output BER of 10^{-12}.

When the polarization of the control-wavelength departs from its optimum value, a residual error-floor is always observable, regardless of received-power. Figure 2(b) depicts the associated curves of “output-BER versus received-power” at the worst-value of control-wavelength polarization. In this case, an error-floor of 10^{-5} manifests itself at the maximum power tolerated by the receiver, when FEC is inactive. By activating the proposed FEC scheme, the error-floor has been practically eliminated; error-free reception is now achievable at -20.5 dBm in the ‘weak’ mode and -21.2 dBm in the ‘strong’ one. Behavior at intermediate values of polarization has been found similar.

Notably, the concatenated-FEC scheme does not only correct the errors induced by polarization drift, but it also improves the performance of the wavelength-converter in terms of input-power at the receiver. To obtain a measure of efficiency, we compute the coding-gain of the proposed FEC-scheme, according to the terms and definitions of the ITU-T recommendation G.975.1 (2004). In particular, the net coding-gain amounts to ~6.5/7.0 dB with FOCUS in ‘weak’/‘strong’ mode respectively, at an output BER of 10^{-12}.

Figure 3 highlights the role of ‘outer’ code (FOCUS) in the concatenated-FEC scheme. As long as the ‘inner’ code (WRAP100) fully handles channel-errors, the ‘outer’ code observes error-free data, and therefore remains idle. When, however, the ‘inner’ code succumbs to an overwhelming error-rate, error-multiplication is observed. It is the task of the ‘outer’ code to eliminate these multiplied-errors to the best possible extent. We demonstrate the corrective action of FOCUS by actually driving WRAP100 to the verge of error-multiplication; this is achievable by modifying the control wavelength polarization. The “output-BER versus input-BER” curves in figure 3 reveal an orders-of-magnitude improvement, fully attributable to FOCUS.

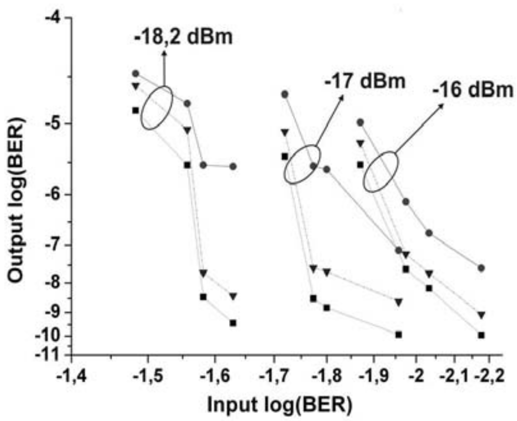

Figure 3: Output-BER versus input-BER curves, when FOCUS is inactive (●), in the ‘weak’ mode (▼) or in the ‘strong’ mode (■).

According to ITU-T recommendation G.975.1 (2004), the performance (NCG) of standard outband-FEC (WRAP100) is theoretically assessed to 5.6dB for an output BER of 10^{-12}. The proposed concatenated-FEC scheme has been found to outperform the above standard by approx. 0.9dB with FOCUS in the ‘weak’ mode and 1.4dB in the ‘strong’ one. This head in performance can be considered as the contribution of FOCUS. FOCUS-gain turns out to be less than half as compared with [6]. This discrepancy is explained by the different role of FOCUS: In [6], FOCUS was the only form of FEC involved and was evaluated against a non-biased transmission-errors distribution (ASE). On the contrary, FOCUS as ‘outer’ code in the proposed concatenated scheme, has to cope with an excessive error-rate, associated with error-multiplication by the ‘inner’ code. Although multiplied-errors have indeed favorable statistics (i.e. appear in bursts), the error-rate is nonetheless overwhelming. We therefore regard this performance as an achievement, taking also the nature of inband-FEC into consideration.

V. Conclusion

Our work builds on the performance evaluation of FOCUS as a stand-alone inband-FEC scheme [6]. We extend this work, by concatenating FOCUS in series with a standard outband-FEC method. The experimental evaluation of the resulting concatenated-FEC scheme reveals a performance improvement, according to the terms & definitions in ITU-T standards. Most importantly, the additional coding-gain as compared to standard FEC is obtained without resorting to a redesign of the optical link e.g. employing more complex and lower code-rate outband-FEC methods. This is an important advantage in dealing with legacy networks.

The concatenated FEC scheme was evaluated in a purposely misadjusted wavelength converter SOA-MZI. Even in this case, the use of FEC ensures error-free wavelength conversion and polarization control unnecessary before the wavelength converter. As a consequence, our results indicate that application of FEC may help to bring all-optical techniques and transparent optical networks closer. FEC encoding may relax the need for the critical adjustment of parameters that are to control in-the-field, when all-optical devices are being used.

Finally, this work is the proof-of-concept of the previously claimed seamless integration of inband-FEC with any other form of outband-FEC [4] [8]. We have demonstrated that the burst-form errors generated by outband-FEC (on the verge of collapse) can quite efficiently be dealt with by our proposed inband-FEC method. FOCUS is presently a mature method and a low-cost solution [9]; it can therefore be applied to SDH/SONET networks in a cost-effective manner. Besides, FOCUS can operate in two modes, 'weak' and 'strong', according to the channel requirements and characteristics, offering the flexibility to trade complexity for performance.

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