IEEE Photonics Journal
An IEEE Photonics Society Publication

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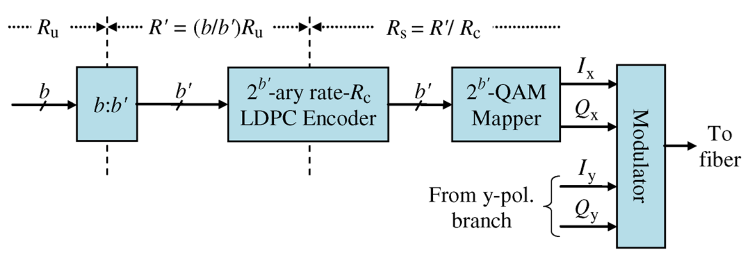
Volume 4, Number 3, June 2012

Murat Arabaci, Member, IEEE
Ivan B. Djordjevic, Senior Member, IEEE
Lei Xu
Ting Wang



DOI: 10.1109/JPHOT.2012.2195777

Nonbinary LDPC-Coded Modulation for High-Speed Optical Fiber Communication Without Bandwidth Expansion

Murat Arabaci,[1] ***Member, IEEE*, Ivan B. Djordjevic,**[1] ***Senior Member, IEEE*,**
Lei Xu,[2] **and Ting Wang**[2]

[1]Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721 USA
[2]NEC Laboratories America, Inc., Princeton, NJ 08540 USA

DOI: 10.1109/JPHOT.2012.2195777
1943-0655/$31.00 ©2012 IEEE

Manuscript received March 20, 2012; revised April 6, 2012; accepted April 12, 2012. Date of publication April 20, 2012; date of current version May 7, 2012. This work was supported in part by the National Science Foundation under Grant CCF-0952711 and in part by NEC Laboratories America, Inc.
Corresponding author: M. Arabaci (e-mail: arabaci@email.arizona.edu).

Abstract: We propose a scheme that can attain the same transmission bit rate as the corresponding conventional polarization-division-multiplexed (PDM) quadrature amplitude modulation (QAM) scheme while occupying lower bandwidth and, hence, achieving a higher spectral efficiency. In contrast to the conventional approach, which increases the symbol rate and thus the occupied bandwidth to transmit the redundant symbols due to forward error correction (FEC), the proposed approach expands the underlying signal constellation in size and reduces the FEC code rate accordingly to form a mechanism that can achieve coded transmission without bandwidth expansion. Such a scheme can find applications in scenarios where there exist stringent bandwidth restrictions and bandwidth expansion is not considered as a viable option. Although the idea of constellation expansion in lieu of bandwidth expansion is mainly associated with Ungerboeck's trellis-coded modulation (TCM), our proposed nonbinary low-density parity-check (LDPC)-coded modulation scheme shows that block-coded modulation schemes can also be used with expanded constellations to achieve transmission without bandwidth expansion and without resorting to TCM. Our results reveal that for small to medium constellation sizes, the proposed scheme can preserve bandwidth while not experiencing significant increase in required optical signal-to-noise ratio (OSNR). For large constellation sizes, however, to keep the increase in required OSNR at manageable levels, we propose using controlled bandwidth expansion where constellation expansion and bandwidth expansion are used simultaneously to obtain a balance between the two critical system parameters of bandwidth and required OSNR.

Index Terms: Coherent communication, coded modulation, fiber optics communication, forward error correction (FEC), low-density parity-check (LDPC) codes.

1. Introduction

To address the increasing demand for higher capacity transmission over optical fiber links, given the bandwidth limitations, the recent trend in optical fiber communications community, including both academia and industry, is toward pushing the spectral efficiency (SE) of transmission higher [1]–[5]. As SE is increased by packing more bits into a transmitted symbol, the constellations get denser and the Euclidean distance (for a given average symbol energy) between constellation points decreases. Consequently, receivers require higher optical signal-to-noise ratios (OSNRs) which might translate into compromising on the system reach and/or the regeneration distance. An effective solution to relax the OSNR requirement is based on forward error correction (FEC). In fact, as SE increases, FEC assumes a more important role in achieving long-haul transmission without resorting to expensive regeneration option. With the advent of coherent detection and digital signal processing, soft FEC with overheads up to 20% are currently being considered for long-haul optical fiber transmission [5]–[7].

Conventionally, the redundant bits of FEC are accommodated for by increasing the symbol rate of transmission, denoted by R_s. It is important to note, however, that an increase in R_s results in bandwidth expansion, i.e., an increased consumption of the rather scarce resource of bandwidth. More explicitly, the occupied bandwidth is proportional to R_s; therefore, the amount of additional bandwidth needed to transport FEC symbols is proportional to $R_s(1 - R_c)$, where R_c is the FEC code rate. Currently, 100-Gb transmission based on quadrature phase shift keying (QPSK) is achieved at 28 GBaud with 7% FEC overhead and at 32 GBaud with 20% FEC, where overhead is given by $O_c = 1/R_c - 1$. Future generations of Ethernet might push symbol rates even higher. Even though symbol rates around 43 GBaud are considered as the most probable candidates [1], [4], systems operating at 80 GBaud symbol rates have already been demonstrated [8]. Assuming that next generation systems will employ the same FEC code rates R_c, it is worth highlighting that systems operating at higher symbol rates will not only require larger bandwidths; they will also need to reserve larger portions of their total occupied bandwidth to transport FEC overhead. In other words, the bandwidth associated with FEC remains constant in terms of percentage with respect to the total occupied bandwidth but it increases as a physical quantity. Although FEC is a crucial tool in achieving long-haul transport at high bit rates, the transmission of FEC overhead comes at the expense of larger bandwidth requirement, which are expected to get more pronounced in future generations of Ethernet that will probably employ higher symbol rates.

In situations where bandwidth expansion is not a viable option, schemes that can operate under stringent bandwidth constraints and continue to provide significant coding gains become crucial. One such technique is Ungerboeck's trellis-coded modulation (TCM) approach [9], [10], where bandwidth expansion is prevented by constellation expansion and by adjusting the code rate accordingly. Recently, Magarini *et al.* [11] applied a concatenated TCM scheme to optical fiber communication which combines an outer block code with an inner TCM code. In this paper, we also expand underlying constellation in size to prevent bandwidth expansion. However, we propose using just a single nonbinary low-density parity-check (LDPC) code rather than using a concatenated TCM framework. Our proposed nonbinary LDPC-coded modulation (NB-LDPC-CM) scheme shows that well-designed block-coded modulation schemes can be used with expanded constellations to achieve optical fiber communication without bandwidth expansion and without resorting to TCM. This is the main contribution of our paper. Furthermore, it is clear that a larger constellation requires a higher OSNR to achieve the same bit error ratio (BER). Our analyses reveal that constellation expansion when applied to small to medium constellations does not cause significant increase in required OSNR. On the other hand, when large constellations are used, the increase in the required OSNR due to constellation expansion becomes substantial. Thus, we propose allowing a controlled amount of bandwidth expansion to reduce the required OSNR. Such a scheme allows for a compromise between the two critical system resources, namely bandwidth and required OSNR. To the best of our knowledge, such a flexible bandwidth expansion idea is also novel to this paper.

The rest of the paper is organized as follows. We start by discussing the peculiarities of our proposed scheme in Section 2. Simulation results are then presented in Section 3, along with discussions on their significance. Finally, Section 4 presents our concluding remarks.

2. Conventional Approach versus the Proposed Approach

The transmitter (Tx) and receiver (Rx) configurations for a conventional, coded, polarization-division-multiplexed (PDM) quadrature amplitude modulation (QAM) scheme can be depicted as in Fig. 1(a) and (b), respectively. These Tx/Rx configurations have already been discussed to a great extent in the literature [2], [4], [7], [12]; hence, we will keep our discussion to the Tx side only to help present the main idea behind the proposed approach. In this paper, we employ nonbinary LDPC

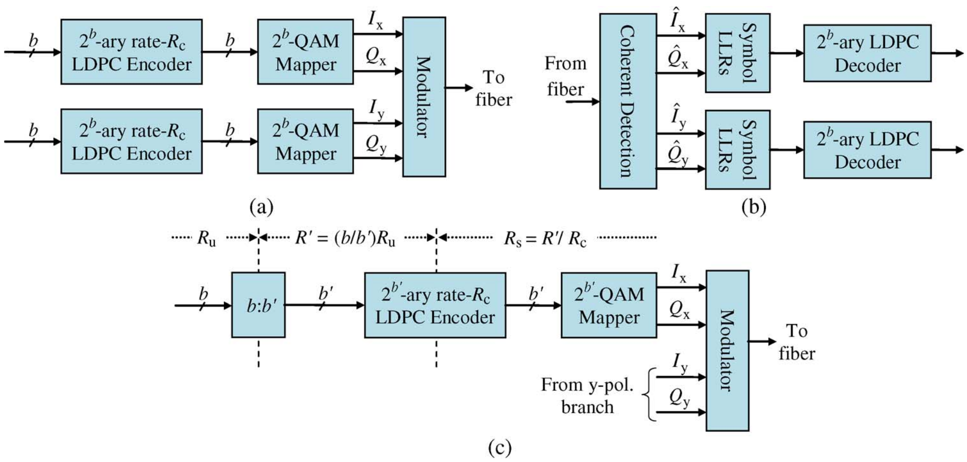


Fig. 1. Block diagram of the Tx (a) and Rx (b) configurations of a 2^b-ary, $b>1$, LDPC-coded modulation with a matching 2^b-ary QAM constellation. (c) Tx configuration for the proposed scheme using an LDPC encoder and a matching QAM constellation over a $2^{b'}$-ary alphabet, where the shift in alphabet size from 2^b to $2^{b'}$ is enabled by a $b:b'$ rate conversion unit, where $b'>b$. Notice that the signals flow at different rates in different regions of the transmitter and these regions and their symbol rates are indicated in the figure with dotted lines.

codes as component codes. As presented in our previous works [13]–[15], compared with bit-interleaved LDPC-coded modulation (BI-LDPC-CM) schemes employing binary component codes, NB-LDPC-CM approach provides much higher coding gains. Indeed, coding gain improvements provided by NB-LDPC-CM over the corresponding BI-LDPC-CM increases as the underlying constellation size (and hence SE) increases, which is one of the reasons why NB-LDPC-CM is expected to stir further interest in the optical communication community as SE continues to gain more importance. In Fig. 1, we use b-bit wire to indicate a 2^b-ary source signal which is tantamount to b parallel binary source signals. As another remark, we should state that the proposed scheme is generic in nature and can be used with virtually any class of FEC codes in addition to LDPC codes. To achieve the same transmission bit rate as the uncoded case, conventional schemes employing FEC transmit data at a higher symbol rate. As shown in Fig. 1(a), following the encoder, which encapsulates the incoming K-symbol information stream into a larger N-symbol codeword, the symbol rate is increased by $1/R_c$, where R_c is the code rate and is given by $R_c = K/N$. In other words, if the information bearing signal is streamed at R_u symbols/s, encoded symbols are transmitted at the symbol rate of $R_s = R_u/R_c$ symbols/s. Thus, the transmission bit rate is given by $2R_sR_c\log_2 M = 2R_u\log_2 M$ bits/s, where M is the constellation size, which is equal to the uncoded transmission bit rate as desired. (Note that the coefficient of 2 comes from polarization multiplexing.)

The proposed scheme offers a different solution with its modified Tx configuration given in Fig. 1(c). First, the incoming 2^b-ary source signal is converted into a $2^{b'}$-ary signal, where $b'>b$, by means of a $b:b'$ rate conversion unit, which converts b parallel binary signals at R_u bits/s into b' parallel binary signals at a lower rate of $R' = (b/b')R_u$ bits/s. Such rate conversion units are mainly based on first-in first-out (FIFO) queues. A familiar example is the (comparatively more complex) $10 \times$ 10-Gb/s to $4 \times$ 25-Gb/s gearbox used in 100-Gb Ethernet (GbE) physical layer as presented in [12] which employs 20 FIFOs in its implementation. (Similarly, we can rephrase $b:b'$ rate conversion unit as a $b \times R_u$ to $b' \times R'$ gearbox.) Another rate conversion takes place within the FEC unit. Upon encoding, the input symbol rate to the encoder, i.e., $R' = (b/b')R_u$ symbols/s, is converted to a higher symbol rate $R_s = R'/R_c = (b/b')R_u/R_c$ symbols/s. In an FEC unit, such a rate conversion operation is commonly implemented using a FIFO block with independent read and write clock domains, as exemplified in [16]. The Rx end of the proposed scheme works in principle the same way as the conventional Rx; however, in the proposed scheme, following $2^{b'}$-ary LDPC decoders, the resulting b' parallel binary signals are converted to b parallel binary signals at the uncoded signal rate of R_u bits/s.

TABLE 1

Comparison between transmission schemes with and without bandwidth expansion

Name	b (bits/sym)	b' (bits/sym)	Code Parameters [a]			Bit Rate (Gbps)	Bandwidth Expansion	Required OSNR (dB) @ 10^{-7}
			R_c	(γ,ρ) [b]	Girth [c]			
PDM-QPSK	2	-	0.833	(3,18)	8	105.28	20%	9.27
NoBWE-8-QAM	2	3	2/3	(3,9)	12	105.28	-	9.71
PDM-8-QAM	3	-	0.833	(3,18)	8	157.92	20%	12.77
NoBWE-16-QAM	3	4	3/4	(3,12)	10	157.92	-	13.53
PDM-16-QAM	4	-	0.833	(3,18)	8	210.56	20%	15.57
NoBWE-32-QAM	4	5	4/5	(3,15)	8	210.56	-	16.95
PDM-32-QAM	5	-	0.833	(3,18)	8	263.2	20%	18.26
NoBWE-64-QAM	5	6	5/6	(3,18)	8	263.2	-	20.47

[a] Code length is fixed at $N = 27216$ symbols for all component codes.
[b] A (γ,ρ)-regular LDPC code has γ nonzero elements in each column and ρ nonzero elements in each row of its parity-check matrix.
[c] Girth is the minimum length cycle in the bipartite (Tanner) graph representation of the parity-check matrix of an LDPC code.

Our scheme can achieve reliable data communication over optical networks while operating at lower symbol rates than the corresponding conventional schemes. It results in reduced bandwidth consumption. There are also added advantages associated with transmission at lower symbol rates and with smaller bandwidths such as relaxed optical filtering requirements, better chromatic dispersion (CD) and polarization mode dispersion (PMD) tolerances and easier nonlinearity management, and cheaper components based on more mature technology. These advantages, however, do not come by without an expense. Mainly due to being based on a larger signal constellation, schemes preventing bandwidth expansion suffer from reduced coding gain, as we will further analyze in Section 3.

In the literature, a similar Tx/Rx configuration that sends data without bandwidth expansion was studied for wireless communication over fading channels [17]. However, the gist of the approach in [17] was to achieve diversity with the help of constellation expansion, which is a totally separate line of thought. Other works, which are more aligned with the incentives we had in proposing our scheme, are due to Magarini *et al.* [11] and Bülow *et al.* [18]. To provide coding gains without bandwidth expansion, the authors in [11] propose a TCM approach as we discussed in the Introduction whereas the idea in [18] is to use an expanded 24-point constellation (six states of polarization and QPSK constellation in each state of polarization). Unlike our scheme which can be used with the conventional I/Q modulators (see Fig. 1(c)), the scheme in [18] requires specialized modulators and detectors to modulate onto and detect from six states of polarization. Furthermore, compared to [18], our scheme is more flexible in the sense that any constellation can be combined with any FEC code. In the context of optical fiber transmission without bandwidth expansion, this paper contributes a novel and practical solution to the problem.

3. Numerical Results and Discussion

We investigate the performance of our approach under amplified spontaneous emission (ASE) noise dominated transmission scenario. The parity-check matrix of a component q-ary LDPC code is constructed by assigning nonzero elements from the finite field of q elements to the 1s in the parity-check matrix of the corresponding binary base code. We employed quasi-cyclic binary LDPC codes designed using cyclic-invariant difference sets (CIDS) as our binary base codes, and constructed nonbinary codes by nonzero element assignment as discussed above. More details on these techniques can be found in [13], [15], [19], and references therein. All the component codes used in our simulations have the same codeword length $N = 27\,216$ symbols to enable fair comparison. Two additional parameters pertaining to the component LDPC codes are also provided in Table 1; namely, the girth, i.e., the length of the shortest cycle in the bipartite graph corresponding to the parity-check matrix of an LDPC code and the regularity structure. Furthermore, we utilized fast Fourier transform (FFT) based decoding algorithm to decode nonbinary LDPC codes and employed the maximum of

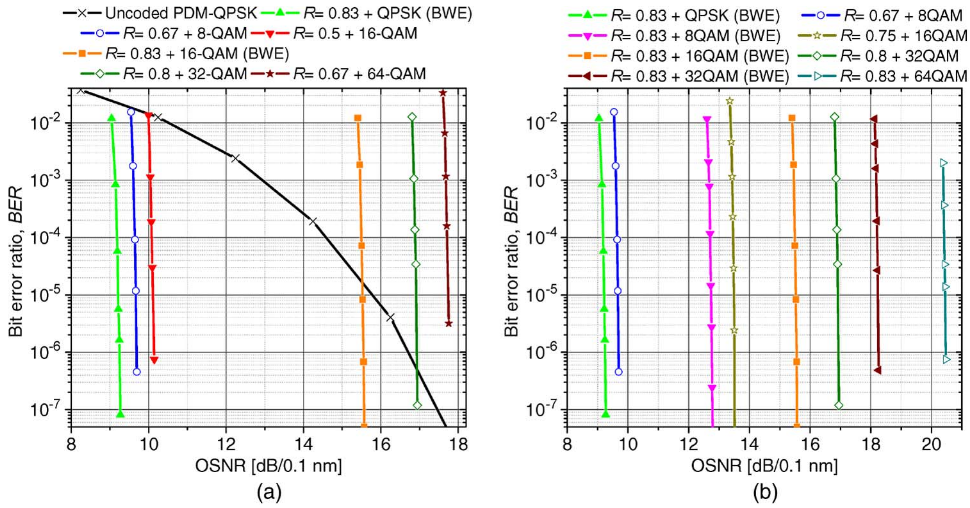


Fig. 2. (a) Comparison between the conventional PDM-2^b-QAM (denoted by "BWE" in the legend) transmitting b coded bits/symbol against the proposed scheme transmitting b' coded bits/symbol with $b' = b + 1$ and $b' = b + 2$. Against PDM-QPSK, the proposed scheme is used with $b' = 3$ (8-QAM and $R_c = 0.67$) and $b' = 4$ (16-QAM and $R_c = 0.5$), and against PDM-16-QAM, it is used with $b' = 5$ and $b' = 6$. (b) Comparison between various PDM-2^b-QAM schemes (denoted by "BWE" in the legend) transmitting b coded bits/symbol against the proposed scheme transmitting $(b + 1)$ coded bits/symbol.

50 decoding iterations. (For more details on the decoding algorithm, see to [13], [15], and references therein.) In our simulations, we fixed the uncoded symbol rate at $R_u = 26.32$ Giga-symbols/s, which is slightly above 25 Giga-symbol/s, to allow for possible framing overhead.

It is of interest first to understand the performance of the proposed scheme when a 2^b-ary constellation gets expanded to a larger $2^{b'}$-ary constellation as b' is varied for a fixed b. As one will recall from Section 2, the symbol rate after encoding is given by $R_s = (b/b')R_u/R_c$. For a fixed b, and a fixed transmission bit rate of $2R_u b$ bits/s, and fixed bandwidth (i.e., no bandwidth expansion), we must have $R_s = R_u$, and hence, the component FEC code must be of rate $R_c = b/b'$. For example, to compare against uncoded PDM-QPSK, we can use the proposed scheme with 8-QAM and an 8-ary LDPC code of rate 2/3, or with 16-QAM and a 16-ary LDPC code of rate 1/2, and so on. The conventional coded modulation approach to compare against these schemes would then be PDM-QPSK with 4-ary LDPC code of code rate 0.833, i.e., overhead of 20%. We should note that to attain the highest possible coding gains in conventional schemes with soft-decision FEC, all the available 20% overhead is generally used [5]–[7]. To make the results we obtained by using soft-FEC with the conventional system setup comparable to those available in the literature, we also adopted 20% FEC in our manuscript. Hereafter, we denote by PDM-2^b-QAM the conventional PDM transmission with the conventional 2^b-QAM constellation and a 2^b-ary LDPC code of rate 0.833 (20% overhead). Further, hereafter, we denote the proposed scheme by NoBWE-$2^{b'}$-QAM to signify that it prevents bandwidth expansion. However, the FEC code rate of the proposed scheme needs to be explicitly stated. Given that we set $R_u = 26.32$ Giga-symbols/s, PDM-2^b-QAM operates at the symbol rate of $R_s = R_u/R_c = 31.59$ Giga-symbols/s. On the other hand, for all NoBWE-$2^{b'}$-QAM schemes the symbol rate is $R_s = (b/b')R_u/R_c = R_u = 26.32$ Giga-symbols/s, i.e., there is no bandwidth expansion, since a larger constellation is being used and code rate is set to $R_c = b/b'$. Note that both schemes attain the aggregate bit rate of $2R_u b$ bits/s. We simulated the performances of the aforementioned schemes and presented our results in Fig. 2(a). As depicted in the figure, PDM-QPSK provides the highest net coding gain (NCG) of about 8.18 dB at the bit error ratio (BER) of 10^{-7}. However, it requires 20% increase in bandwidth. NoBWE-8-QAM, which is the proposed scheme used with the 8-QAM constellation and a rate-2/3 8-ary LDPC code, performs 0.44 dB worse than PDM-QPSK at the same BER. Furthermore, this difference in NCG increases to 0.9 dB at the BER of 10^{-7} if NoBWE-16-QAM with rate-1/2 16-ary LDPC code is used instead. Thus, for a fixed b, e.g., $b = 2$ above, we can assert that increasing the constellation size used in the proposed scheme degrades performance. In other words, for transmission at the same aggregate bit rate, the performance degradation that the proposed scheme experiences due to constellation expansion cannot be counteracted by the performance improvement gained by employing FEC with a reduced code rate. In another set of simulations, we also compared PDM-16-QAM against the corresponding schemes based on the proposed approach. As shown in Fig. 2(a), increasing b' from 5 (i.e., NoBWE-32-QAM) to 6 (i.e., NoBWE-64-QAM) further opens the performance gap to PDM-16-QAM performance curve, which confirms our assertion above. Considering also the fact that the complexity of q-ary LDPC decoders scales with $q\log q$ [13], [15], we can conclude that when setting up a NoBWE-$2^{b'}$-QAM scheme corresponding to PDM-2^b-QAM based on the proposed approach, using $b' = b + 1$ is the best choice from both performance and complexity standpoints.

To deepen our understanding, we performed additional simulations. In accordance with our observations above, we used in our current simulations NoBWE-2^{b+1}-QAM scheme with rate-$(b/(b+1))$ FEC code on each polarization branch when performing comparisons against PDM-2^b-QAM. We compared PDM-QPSK, PDM-8-QAM, PDM-16-QAM, and PDM-32-QAM against the corresponding schemes based on the proposed approach. Our simulation results are presented in Fig. 2(b). We can deduce from the figure that the performance gap between the conventional scheme and the proposed scheme increases as the underlying constellation grows in size. This is consistent with our observation in Fig. 2(a) that, against PDM-2^b-QAM, using b' larger than $b + 1$ in NoBWE-$2^{b'}$-QAM exacerbates performance. To state it numerically, PDM-8-QAM provides 0.74 dB more coding gain than NoBWE-16-QAM with $R_c = 0.75$. This difference in coding gain increases to 1.38 dB in PDM-16-QAM versus NoBWE-32-QAM with $R_c = 0.8$ comparison and jumps to 2.21 dB in PDM-32-QAM versus NoBWE-64-QAM with $R_c = 0.833$ comparison. (All comparisons are made at the BER of 10^{-7}.) Table 1 presents these comparisons in a more compact form.

We observe that when replacing the conventional PDM-M-QAM schemes causing bandwidth expansion with a scheme like ours preventing bandwidth expansion, the performance penalty increases as the underlying constellation size M increases. Consequently, the proposed scheme can be aptly used with small to medium size constellations without incurring significant OSNR penalty. On the other hand, for large constellations, our analysis suggests that the amount of bandwidth preserved by adopting a scheme without bandwidth expansion and the amount of increase in the required OSNR should be balanced. Such a balance can be achieved by introducing a controlled amount of bandwidth expansion. The proposed scheme lends itself very easily to such a controllable bandwidth expansion approach since the FEC code rate after constellation expansion can be reduced to a value lower than b/b' to increase FEC strength (and, hence, lower the OSNR requirement) while increasing the occupied bandwidth proportionally.

4. Conclusion

We proposed a scheme enabling transmission at the same aggregate bit rate as the conventional PDM-QAM scheme while operating at a lower symbol rate and occupying smaller bandwidth. Having reduced occupied bandwidth, the proposed scheme relaxes the stringent requirements in optical filters present in the link. Furthermore, it increases immunity to impairments due to CD, PMD and fiber nonlinearities owing to its operating at a lower symbol rate. In addition, the components operating at lower symbol rates are generally cheaper due to being based on a more mature technology. These benefits offered by the proposed scheme come at the expense of reduced net coding gains. Taking into account its advantages mentioned above, our analysis show that such a penalty in coding gain is acceptable for small to medium size constellations; however, it increases to a level that renders the proposed scheme implausible for large constellations. In the latter cases, our scheme can be used to introduce controlled amount of bandwidth expansion where the penalty in coding gain can be reduced by employing FEC codes with lower code rates than b/b' when constructing NoBWE-$2^{b'}$-QAM corresponding to PDM-2^b-QAM, trading off bandwidth for reduction in required OSNR to attain a balance between these two critical system resources. A natural extension of this current work would be toward investigating the prospects of the proposed scheme in an experimental setup and during long-haul transmission.

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