Extending the Reach of Optical Interconnects with Advanced Coded Modulation

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***Abstract*—An advanced coded modulation is proposed based on improved staircase codes using marked bits and geometrically-shaped constellations. Up to 0.95 dB SNR gain and 8.6% reach increase are achieved for beyond 800G data center interconnects.**

***Index Terms*—Coded modulation, forward error correction, staircase codes, data center interconnects**

I. Introduction

To meet the explosively increasing data demand, the optical transport industry is now in the process of leveraging the 400ZR standard to define 800G coherent optical standard for data center interconnects (DCIs). To reach 800 Gbps transmission over a single wavelength, higher order modulations (e.g., 32QAM and 64QAM [1]), higher gain forward error correction (FEC) [2], and higher symbol rates of 90 Gbaud or more need to be considered. The combination of modulation format and FEC is also known as coded modulation (CM), which is of key importance to boost the improvement of the reliably transmitted data rate and transmission reach per channel.

One approach to improve the performance of CM system is to employ signal shaping, including probabilistic shaping (PS) [3], geometric shaping (GS) [4] and a combination of the two [5]. These techniques are often used to mimic Gaussian distribution on the symbols by either changing the probability or the position of the constellation points, compared to conventional QAM formats. Compared to GS, PS in general has better performance improvement in additive white Gaussian noise (AWGN) channel and greater flexibility [6], but requires an external distribution matcher with an efficient implementation. By contrast, GS straightforwardly modifies the mapper and demapper of the CM system and is easily coupled with FEC and designed for different impairments (e.g., fiber nonlinearity [7] and laser phase noise [8]).

Due to complexity constraints at high data rate, FEC solutions with hard-decision (HD) decoding are preferred for 400 Gbps and beyond optical transport networks (OTNs). Staircase codes (SCCs) [9], which are one of the popular zipper representation codes [10], are spatially-coupled FEC schemes based on algebraic BCH component codes and iterative bounded distance decoding (BDD). Benefiting from low complexity and high coding gain, SCCs to date have been recommended in G.709.2/Y.1331.2 standard for 100G long-reach OTNs [11], OIF Implementation Agreement for 400ZR [12], and etc. In recent years, several works have shown that the performance of SCCs can be further enhanced by for example checking conflicts [13], error-and-erasure decoding [14] and marking bits [15], [16] to prevent BDD miscorrection and/or to extend error-correcting capability, and solving stall patterns via bit flipping [17]. Among these methods, the class of soft-aided HD decoding schemes [14]–[16] is the most popular one, which uses channel soft information to assist HD decoding and provides a good performance-complexity tradeoff.

In this paper, an advanced CM scheme is proposed by combining geometric shaping with enhanced SCC using improved soft-aided bit-marking (iSABM) algorithm, which is referred as GS-iSABM-SCC. In particular, the positions of the GS constellation points and the mapping strategy are optimized in terms of generalized mutual information (GMI), while the iSABM algorithm slightly uses soft information to mark bits via two reliable thresholds to improve the decoding of SCCs. When compared to the existing CM system based on MQAM ($M = 32, 64$) and conventional decoding of SCCs, the proposed GS-iSABM-SCC can provide up to 0.95 dB SNR gain over AWGN channel and up to 8.6% reach increase over optical fiber channel for data rates between 800 and 888 Gb/s per wavelength.

II. System Model and the Proposed Improved Coded Modulation Scheme

A. System Model

The system model of the proposed CM scheme in this paper is shown in Fig. 1. Information bits are encoded by an SCC encoder (with code rate R), which is composed by a sequence of $w \times w$ blocks organized like a staircase [15, Fig. 1]. Each row of two neighbor SCC blocks is a valid BCH component codeword with parameters (n, k, t), where n is the codeword length, k is the information length, and t is the error-correcting capability determined by the minimum Hamming distance d_0 between the BCH codeword (i.e., $t = \lfloor (d_0 - 1)/2 \rfloor$). After perturbation by an interleaver, every m bits are mapped to symbol x_l taken from MQAM or MGS ($M = 2^m$) constellation $\mathcal{X} = \{s_1, s_2, \ldots, s_M\}$, where l is the discrete time index. After transmission over channel, the receiver estimates the transmitted bits using an HD-based

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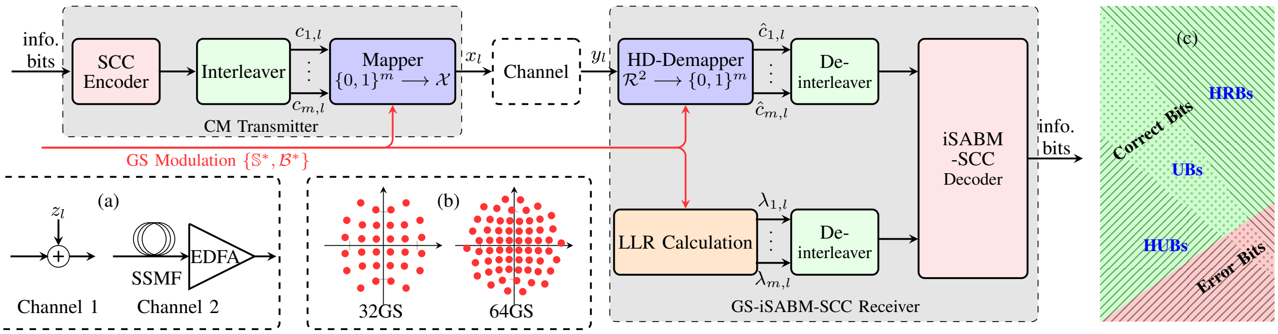


Fig. 1: System model considered in this paper: (a) considered channel models, (b) geometrically-shaped constellations for $M = \{32, 64\}$, and (c) an illustration to indicate the relationship between the marked bits and the received bits.

demapper and calculates the soft information $\lambda_{1,l}, \ldots, \lambda_{m,l}$ for the m bits per symbol, according to the detected signal y_l and the transmitted modulation format. After being restored to their original order by a deinterleaver, the HD-estimated bits $\hat{c}_{1,l}, \ldots, \hat{c}_{m,l}$ and the LLRs $\lambda_{1,l}, \ldots, \lambda_{m,l}$ will be both sent to the SCC decoder for error correcting.

In this paper, two kinds of channels are considered: AWGN channel and single-span optical fiber channel, as shown in Fig. 1(a). In the AWGN channel, the received signal is given by $y_l = x_l + z_l$, where z_l is circularly-symmetric complex Gaussion noise with zero mean and N_0 variance. The signal-to-noise ratio (SNR) is defined as $\text{SNR} = E_s/N_0$, with $E_s \triangleq \mathbb{E}[x_l^2] = (1/M)\sum_{i=1}^{M} s_i^2 = 1$, where $\mathbb{E}[\cdot]$ denotes expectation.

The second one is the optical fiber link consisting of standard single-mode fibers (SSFMs) cascaded with erbium-doped fiber amplifiers (EDFAs). The transmission performance of the fiber link is evaluated based on GN model [18], but modified by introducing noise in the transmitter (Tx). Therefore, the SNR for the considered ith WDM channel at the receiver is written as $\text{SNR}_i \approx P_i/(P_{\text{Tx}_i} + P_{\text{ASE}_i} + P_{\text{NLI}_i})$, where P_i is the transmitted signal power, P_{Tx_i} is the noise power from the transmitter, P_{ASE_i} is the amplified spontaneous emission (ASE) noise power from the optical amplifier and P_{NLI_i} is the fiber nonlinear interference (NLI). Particularly, the noise power in the transmitter P_{Tx_i} is roughly estimated by considering the required minimum 34 dB/0.1nm in-band optical SNR for 400ZR [12] and -7 dBm transmitting power [19] at the transmitter side.

B. Improved Coded Modulation

As Fig. 1 shows, the proposed GS-iSABM-SCC CM scheme is composed of GS modulation format and SCC with iSABM decoding to jointly provide shaping gain and coding gain, while keeping the complexity as low as possible.

For GS constellation designing, GMI, which is the most popular achievable information rate (AIR), is considered as the cost function to optimize the modulation format $\mathcal{X}$. Let $f_{\boldsymbol{Y}|\boldsymbol{X}}$ be the channel law, $\mathcal{X}$ and $\mathcal{L}$ be the initial constellation and the corresponding labeling, the optimization problem to find the optimal constellation $\mathcal{X}^*$ and $\mathcal{L}^*$ can be written as

$$\{\mathcal{X}^*, \mathcal{L}^*\} = \underset{\mathcal{X},\mathcal{L}: E[\|\boldsymbol{X}\|^2] \leq E_s}{\arg\max} \; G(\mathcal{X}, \mathcal{L}, f_{\boldsymbol{Y}|\boldsymbol{X}}) \tag{1}$$

where $G(\mathcal{X}, \mathcal{L}, f_{\boldsymbol{Y}|\boldsymbol{X}})$ represents GMI. Note that we consider only one of the polarizations for the shaping optimization. Fig. 1(b) shows the optimized results for $M = 32$ and $M = 64$ GS constellations over AWGN channel with SNR of 15 dB and 19 dB, respectively.

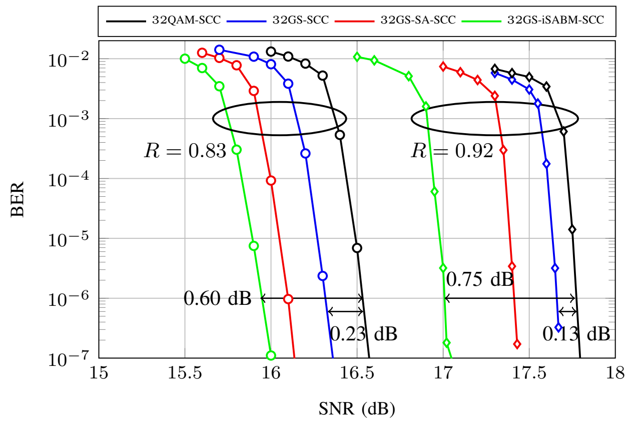
For the iSABM-SCC decoder, sliding window fashion is performed with window length of L. Within each window, the decoding of the last $L-K$ blocks is improved by the iSABM algorithm, while the decoding of other blocks is still performed by BDD, where $K = 0, \ldots, L-2$. By contrast, standard SCC simply performs BDD for all L blocks. The key of iSABM algorithm is bit marking, in which two reliability thresholds are required. Let δ_1 and δ_2 ($\delta_1 \geq \delta_2 \geq 0$) be the thresholds for highly reliable bit (HRB) and highly unreliable bit (HUB), respectively, the marked result for bit $\hat{c}_{i,l}$ is given by

$$\begin{cases} \text{HRB}, & \text{if } |\lambda_{i,l}| \geq \delta_1 \\ \text{UB}, & \text{if } \delta_2 \leq |\lambda_{i,l}| < \delta_1 \\ \text{HUB}, & \text{if } |\lambda_{i,l}| < \delta_2 \end{cases}, \tag{3}$$

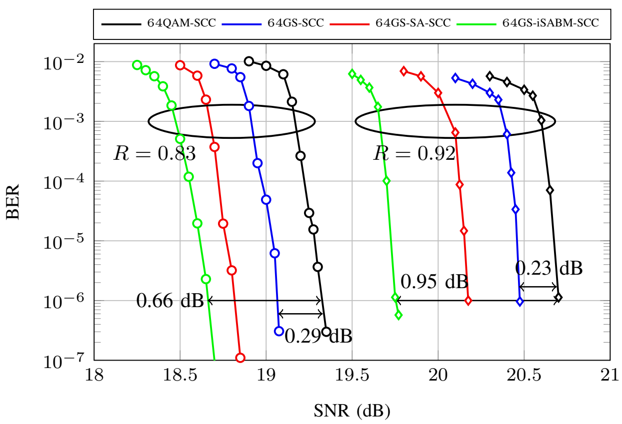
where $|\lambda_{i,l}|$ denotes the absolute value of $\lambda_{i,l}$. Fig. 1(c) illustrates the relationship between the marked bits and the received bits. The green area and red area represent the received correct and error bits, respectively, while the pattern-filled regions in the top, middle and bottom are the marked HRBs, uncertain bits (UBs) and HUBs, respectively.

With the marked HRBs, the iSABM algorithm identifies and prevents BDD miscorrections by checking conflict between the HRBs and the detected errors. That is, once any HRB is involved in the detected errors for the BDD success case, the output of BDD will be regarded as a miscorrection and be rejected. In addition, the detected errors shouldn't conflict with the zero-syndrome component codewords as well. Otherwise, the corresponding BDD output will be regarded a miscorrection as well.

With the marked HUBs, the iSABM algorithm will try to correct more than t errors by randomly flipping HUBs. Specifically, when the first BDD is performed, the decoder will randomly flip $d_0 - w_{\text{H}}(e) - t$ HUBs and 1 HUB for the detected miscorrections and failures, respectively, to try to correct part of errors in the received sequence in advance, where $w_{\text{H}}(e)$ is the Hamming weight of the error pattern e detected by BDD. As a result, when second BDD is performed, there is a

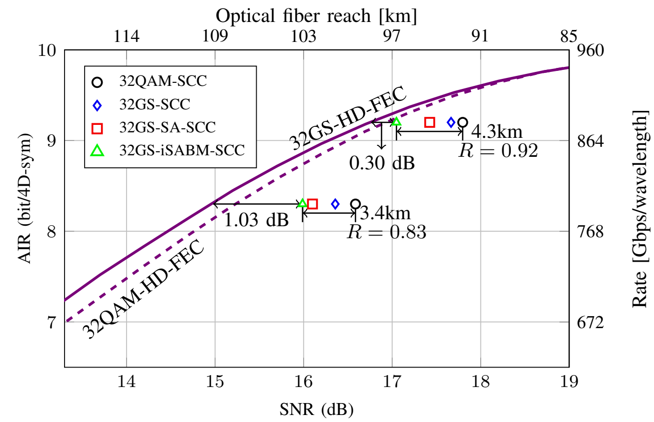


(a) 32QAM and 32GS

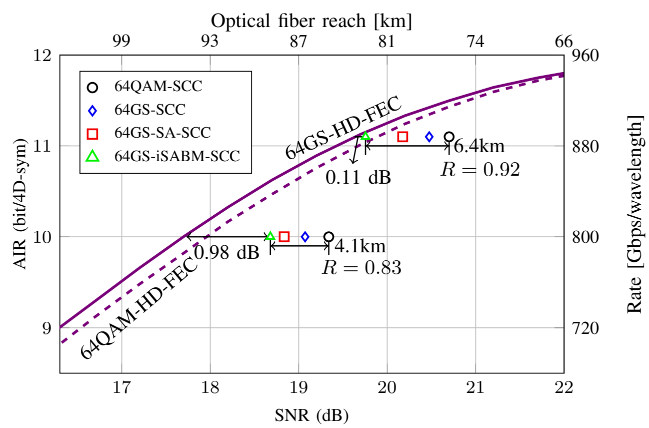


(b) 64QAM and 64GS

Fig. 2: BER performance of the proposed GS-iSABM-SCC CM scheme of (a) 32QAM/32GS and (b) 64QAM/64GS combined with $R = \{0.83, 0.92\}$ FEC code rates.



(a) 32QAM and 32GS



(b) 64QAM and 64GS

Fig. 3: AIR vs. SNR and operational rate vs. optical fiber transmission reach for dual-polarization I/Q-modulation with (a) 32QAM/32GS and (b) 64QAM/64GS constellation points.

probability that the originally uncorrectable sequence (i.e., the cases with more than t errors) can be successfully decoded.

III. Performance Analyses And Discussions

A. *Performance Analyses*

Fig. 2 shows the BER performance of the proposed GS-iSABM-SCC scheme based on MGS modulation formats with $M = \{32, 64\}$ and iSABM-based SCC with $R = \{0.83, 0.92\}$. The two considered SCCs are constructed based on shortened BCH codes with parameters $(228, 209, 2)$ and $(504, 485, 2)$ for $R = 0.83$ and $R = 0.92$, respectively. The SCC decoding window length is $L = 8$ and the value of K is 3 for the iSABM-SCC decoder. The marking thresholds we used are $\delta_1 = 6.4$ and $\delta_2 = 1.8$, which is optimized for SCC based on $(228, 209, 2)$ BCH code at SNR of 15.85 dB. The performance of MQAM combined with standard SCC decoding (MQAM-SCC), MGS combined with standard SCC decoding (MGS-SCC), and MGS with SABM decoding (MGS-SA-SCC) proposed in [20] are also shown in the figures as three baselines. As can be seen, when given a BER threshold of 10^{-6}, GS can provide up to 0.29 dB SNR gain, comparing to 64QAM in combination with standard SCC decoding. By combining GS with the iSABM decoding, the achieved additional gain can be increased to up to 0.95 dB. The achieved gains are significantly larger than that of the GS-SA-SCC sceheme proposed in [20].

Fig. 3 (markers) shows AIR against SNR (x-axis at the bottom) of the investigated CM schemes when BER of 10^{-6} is treated as "error-free" transmission. The AIR for the practical CM scheme is calculated by $2mR$, where the factor of 2 represents the two polarizations of the optical signal. The dashed line gives the AIR upper bound for QAM with HD FEC, while the solid line on the top is the AIR upper bound for GS with HD FEC. They are calculated via $I_{\text{HD}} = 2m(1 + p\log_2 p + (1-p)\log_2(1-p))$, where p is the average pre-FEC BER across the m bits mapped to the QAM or GS modulation format. We can see that the proposed GS-iSABM-SCC can reduce the SNR gap of SCCs to the AIR preditions to 0.30–1.03 dB and 0.11–0.98 dB for $M = 32$ and $M = 64$ with code rates between 0.83 and 0.92, respectively.

Fig. 3 also shows the operational rate against optical fiber transmission reach (x-axis at the top). The simulation parameters for the optical channel are listed in Table I. We can see that the achieved extra gains of GS-iSABM-SCC can yield up to 6.4 km (8.6%) reach increase for data rates between

TABLE I: Simulation parameters of the optical fiber link.

Parameter	32QAM/32GS	64QAM/64GS
Number of WDM channels	40	45
Symbol rate	96 GBaud	80 GBaud
Channel spacing	100 GHz	87.5 GHz
EDFA noise figure	5.5 dB	
Center wavelength	1550 nm	
Attenuation	0.2 dB/km	
Nonlinearity parameter	1.3 $\mathrm{W}^{-1}\mathrm{km}^{-1}$	
Dispersion parameter	17 ps $\mathrm{nm}^{-1}\mathrm{km}^{-1}$	

TABLE II: Numerical results of α_{HRB}, β_{HRB}, α_{HUB} and β_{HUB} for the proposed GS-iSABM-SCC at BER of 10^{-4}.

Modulation	32GS		64GS	
Code Rate R	0.83	0.92	0.83	0.92
SNR (dB)	15.85	16.95	18.55	19.70
α_{HRB}	38.89%	43,42%	39.11%	43.52%
β_{HRB}	99.99%	99.99%	99.99%	99.99%
α_{HUB}	84.81%	83.95%	84.98%	84.14%
β_{HUB}	29.31%	29.19%	29.41%	29.27%

800 Gb/s and 888 Gb/s per wavelength, when compared to the system using QAM and standard SCC.

B. Discussions

For the iSABM algorithm, we can define four probabilities, including (i) the probability α_{HRB} that the correct bit is marked as an HRB, (ii) the probability β_{HRB} that the HRB is a correct bit, (iii) the probability α_{HUB} that the error is marked as an HUB, and (iv) the probability β_{HUB} that the HUB is an error. Table II shows the numerical results of the four probabilities for the proposed GS-iSABM-SCC with $M = \{32, 64\}$ and $R = \{0.83, 0.92\}$ at a post-FEC BER of 10^{-4}. Ideally, the values of α_{HRB} and β_{HRB} had better to approach 100% to perfectly prevent BDD miscorrections and to avoid to mistakenly reject the truly BDD success cases, respectively. At the same time, the values of α_{HUB} and β_{HUB} also had better to approach 100% to correct more errors and to improve the effectiveness of bit flipping, respectively. However, the results given in Table II show that in addition to β_{HRB} and α_{HUB}, the values of α_{HRB} and β_{HUB} need to be further improved. In particular, the value of β_{HUB} currently is only around 29% under the condition of $\delta_2 = 1.8$, indicating a quite low probability to correct error via flipping bit. Therefore, designing an efficient way using extra information to improve the four probabilities is necessary to keep enhancing the performance of the proposed GS-iSABM-SCC. This would be an interesting topic for future work.

IV. Conclusions

In this paper, we present a new coded modulation scheme based on improved soft-aided staircase codes and geometric shaping. The analyses are performed in terms of achievable information rates, optical transmission reach and post-FEC BER. Compared to standard SCC decoding with traditional QAM, up to 0.95 dB SNR gain and 8.6% reach increase are achieved. The results well indicate that the proposed coded modulation scheme provides an efficient way to extend the optical transmission reach for beyond 800G data center interconnects.

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