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Joint Source–Channel Coding via Compressed Distribution Matching in Fiber-Optic Communications

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Abstract: The variability of source entropy due to data idling is inconsistent with most studies' assumptions in probabilistic shaping. We propose a distribution matcher sensitive to the source entropy, and discuss its impacts on fiber-optic communications.
OCIS codes: (060.2330) Fiber Optics Communication; (060.4080) Modulation

1. Introduction

Recently, probabilistic shaping (PS) has attracted interest to extend the reach and enhance the granularity of the spectral efficiency in fiber communications [1,2]. In typical PS systems, the incoming source information bit sequence to the distribution matching (DM) step is assumed to be uniform and independent [1]. The commonly used constant composition DM (CCDM) [3] realizes a fixed probability mass function (PMF) of the transmitted symbols, which does not depend on the input bit sequence. In most PS systems, the PMF of the transmitted symbols would be, at least approximately, targeted to a quantized Gaussian distribution [4], which is almost matched to the channel [1,2]. Here we will study the impact of a varying source entropy, which is rarely done in fiber-optic communications. An optimal encoder, which minimizes the rate loss in the conversion process, can be achieved in two steps, by first applying source coding (often called "compression") and then applying DM. In the standards, simply bit scrambling (flipping bits by applying the XOR operation with a pseudo-random bit sequence) has been used to balance the mark and space counts [5]. Often we tend to assume the source bits as just uniform and independent, although the true source entropy before bit scrambling is variable and dependent on the user traffic, e.g., due to the existence of idle frames in the media access control protocol [5].

Here we, for the first time to the best of our knowledge, apply joint source–channel coding (previously studied in communication theory, e.g., in [6,7]) to fiber-optic communications. It is enabled by a DM that is sensitive to the source entropy. Our recently proposed hierarchical DM [8,9], which is a low-complexity fixed-length to fixed-length conversion, is applicable for this purpose without significantly increased complexity. The proposed technique can reduce the rate losses associated with source and channel coding compared to CCDM, or the better performance is used for reducing power consumption by saving forward error correction (FEC) performance. For further reduction of the rate loss and power consumption (including from nonideal FEC coding [10]), the combination with a minimal-size constellation template for PS is also examined.

2. Proposal of compressed DM

The common Gray code for quadrature amplitude modulation (QAM) consists of amplitude bits and sign bits, the latter being of no interest in PS. Thus here we focus on the amplitude bits only for simplicity. Fig. 1 shows the schematic of code processing before FEC encoding in PS-QAM systems. The incoming source bit sequence $[S_1S_2\ldots]$ can have idle frames [5], consisting of many '0's, which makes the entropy per bit $H(S_i) < 1$. For this reason, non-PS systems historically include bit scrambling. If applied also in a PS system, such preprocessing converts the bit sequence into a balanced one $[A_1A_2\ldots]$ with $H(A_j) = 1$. The DM generates the shaped bit sequence $[D_1D_2\ldots]$, which determines the sequence $[\boldsymbol{X}_1\boldsymbol{X}_2\ldots]$ of two-dimensional input symbols to the fiber channel. In the following, we will drop the bit/symbol indices such as i, j, and k.

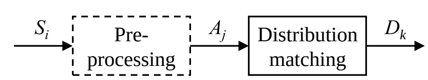
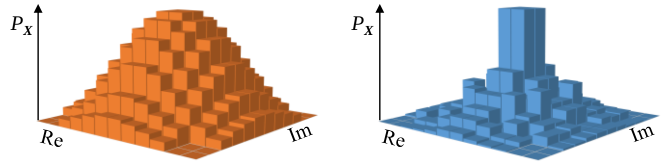


Fig. 1. Code processing before FEC encoding in PS-QAM systems

As a DM which generates a fixed PMF $P_{|\boldsymbol{X}|}$, we consider the example of CCDM. The rate loss in CCDM can be negligible when $H(S) = 1$ and the CCDM word length, N_s, is sufficiently high, typically around 1000. In that case the DM rate loss ΔR_{dm} is defined as $H(|\boldsymbol{X}|) - N_{in}/N_s$, where N_{in} is the number of information bits per input word to the DM. In the case of $H(S) < 1$, ΔR_{dm} should generalize to $H(|\boldsymbol{X}|) - H(S)N_{in}/N_s$. The CCDM will not realize a small rate loss ΔR_{dm} even if N_s is large, because of the constant $H(|\boldsymbol{X}|)$. In some non-constant-composition DMs, bit scrambling is needed as a preprocessing if we desire a fixed $P_{|\boldsymbol{X}|}$. To reduce ΔR_{dm} in the case of $H(S) < 1$, compression of the incoming data is an option, at the expense of, possibly large, digital signal processing circuit resources, since it has to adapt to the time variation of $H(S)$.

However, as we will see, the PMF $P_{|X|}$ is not required to be constant. Our recently proposed hierarchical DM [8,9] can be used for joint source–channel coding, meaning automatic compression of DM input data and PS for lower required signal-to-noise ratio (SNR), by suitably arranging the look-up tables. We sort the DM input word list from the word with the smallest to largest mark ratio, and sort the DM output word list from the word with the smallest to largest energy. Then the expected DM output energy will be controlled by the DM input mark ratio. Fig. 2 shows the resulting PMF P_X for different $H(S)$ cases. The smaller mark ratio input to the hierarchical DM, $P_A(1)$, results in smaller symbol entropy $H(\boldsymbol{X})$ and smaller average symbol energy E. The right-hand side (blue) figure is not a sampled Gaussian distribution. Instead, $H(\boldsymbol{X})$, E, and the required SNR are all less than those of the left-hand side figure (orange). There may be situations with a predominance of ‘0’s (due to many idle frames) or ‘1’s (due to an alarm indication signal, AIS) [5]. In each case, the source entropy is small, although a large mark ratio is not desirable in this proposal. Therefore, to reduce the mark ratio $P_A(1)$ in case of many ‘1’s, all source bits in a suitable block length are flipped to make the DM input mark ratio $P_A(1) \leq 0.5$. The flipping information is carried as an overhead and used at the receiver side for recovering the original data.



$P_A(1) = 0.5$, $H(A) = 1$ (~$H(S)$), $H(\boldsymbol{X}) = 6.68$, $E = 50.9$

$P_A(1) = 0.2$, $H(A) = 0.72$ (~$H(S)$), $H(\boldsymbol{X}) = 6.23$, $E = 38.7$

Fig. 2. PMF of PS-QAM for small or large source entropy $H(S)$ (~$H(A)$).

The time-variable $H(\boldsymbol{X})$ can cause practical issues with respect to electrical amplitude, optical power, and SNR control in the fiber-optic communication systems. Analysis and control method development to account for such issues is deferred to future work, though the variation of $H(\boldsymbol{X})$ per optical wavelength channel would be statistically relaxed by massive optical channel multiplexing.

3. Probabilistic shaping with the minimal constellation template

In most examples of PS, square QAM such as 64-QAM, with an even number of bits per symbol, tends to be used for the constellation template [2,10]. Co-use of the same modulation formats for various rates would make the optical transceiver design and evaluation easier; however, there are also drawbacks. The first drawback is the FEC throughput increase [8,9], which is determined by the output/input rates of the DM. If there is a significant gap between the spectral efficiencies of the shaped constellation and the template, the throughput increase becomes significant. For example, PS-32-QAM has 20% less throughput and less power consumption than PS-64-QAM. This leads to larger power consumption in the FEC coding and decoding circuitry. A second drawback is rate loss due to nonideal FEC performance [10], and a third is analog signal distortion including higher modulator losses. Clearly, low-order modulation is more robust to transceiver imperfections. PS usually increases the peak-to-average power ratio, and it increases the modulation loss and reduces the received optical SNR.

There are a few reports about QAM-based PS with an odd number of bits per symbol, e.g., hybrid geometric-PS 32-QAM [11]. PS-32-QAM would work better in the regime between 4 and 5 bit/symbol. Hierarchical DM can also benefit from odd-QAM-based PS; by sorting the list of DM output words from the smallest to largest energy. Note that, in the case of odd QAM, soft demapping can be performed by a look-up table [12] converting the quantized received in-phase/quadrature amplitudes to *a posteriori* L-values. Considering the implementation of soft demapping, one- or two-dimensional constellations have reasonable table sizes. This minimal constellation template helps minimize the DM rate loss and power consumption in joint source–channel coding by compressed DM.

4. Simulations

We simulated the proposed compressed DM realized by sorting the list of hierarchical DM output words. The constellation template was chosen from 8, 16, 32, 64, or 128-QAM, with N_s = 256, 256, 192, 128, or 128 symbols, resp., and a PS redundancy around 7%. As the 8-QAM constellation, C_3 in [13] was used to make the constellation symmetric around the imaginary axis, so that the uniformly distributed FEC parity bits could be placed on the sign bit without changing $P_{|X|}$. The source mark ratio $P_S(1)$ was varied from 0.05 to 0.5. The AIS and the bit flipping in Sec. 2 was not considered here for simplicity, and we just assumed $P_A(1) = P_S(1) \leq 0.5$. We also simulated FEC decoding for power consumption study. Here we used the DVB-S2 low-density parity check code having a code rate of 5/6, with a maximum number of decoding iterations of 50.

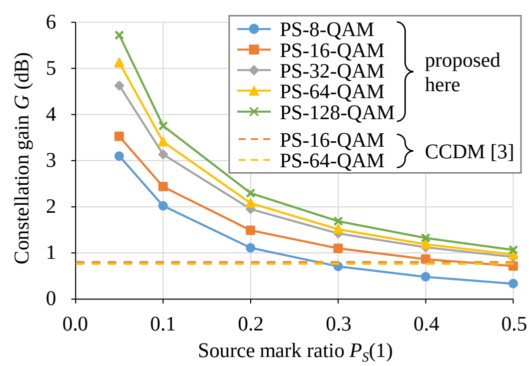


Fig. 3. Constellation gain G vs. source mark ratio $P_S(1)$.

Fig. 3 shows the simulated constellation gain $G = (2^\beta - 1)\, d_{min}^2 / 6E$ [4], where d_{min} is the minimum Euclidean distance. Here we defined the spectral efficiency β as (number of sign bits + N_{in}/N_s). The increasing G for lower values of $P_S(1)$ comes from the reduced average symbol energy E, which is exemplified in Fig. 2, while β and d_{min} remain unchanged. For many idle frames with $P_S(1) < 0.2$, another 1 dB gain or more is seen. The constellation gain G is constant when CCDM is used, which is comparable at $P_S(1) = 0.5$ but less good at smaller values of $P_S(1)$. Note that the two CCDM cases overlap, and uniform (non-PS) 16/64-QAM with bit scrambling would give 0 dB for all $P_S(1)$ conditions, although it is not shown in the figure.

Fig. 4 shows the simulated required SNR with the maximum number of FEC decoding iterations. The PMF assumed in the soft demapping was set to a fixed P_X at $P_S(1) = 0.5$ (possibly mismatched to a higher source entropy for the proposed DM shown by a solid line). For reference, it was also set to P_X (matched to the true source distribution in each case, shown by a dotted line). As shown in Fig. 3, the required SNR can be reduced by the proposed compressed DM in contrast to the fixed required SNR by CCDM and uniform QAM with bit scrambling (due to the fixed P_X). The SNR penalty by the mismatched decoding is not significant except for very $P_S(1)$ cases.

Fig. 5 shows the relative power consumption (calculated from number of decoding iterations) of the FEC decoding for PS-QAM with $P_S(1) = 0.5$ (circle), 0.4 (square), 0.3 (diamond), 0.2 (triangle), 0.1 (cross), or 0.05 (plus), so there are six curves for each QAM order with the proposed DM. The soft demapping was assumed to be mismatched as in Fig. 4, i.e., optimized for $P_S(1) = 0.5$. While CCDM consumes a fixed power even if $P_S(1)$ is reduced (this is the same for non-PS signaling with bit scrambling, but not shown in Fig. 5), the proposed compressed DM significantly reduces the power to about 10%, because of the lower required SNR, which leads to a smaller number of decoding iterations.

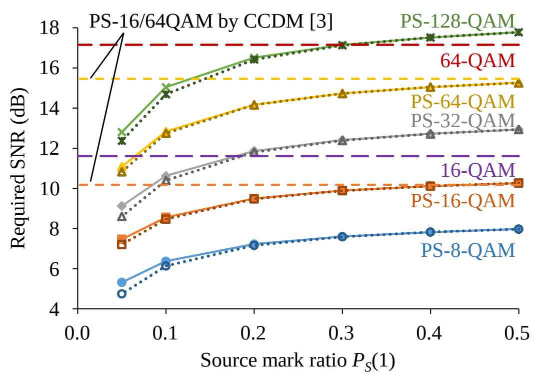


Fig. 4. Simulated required SNR. Solid (dotted) lines illustrate mismatched (matched) decoding with the compressed DM. Dashed (or long-dashed) lines correspond to CCDM (or no PS).

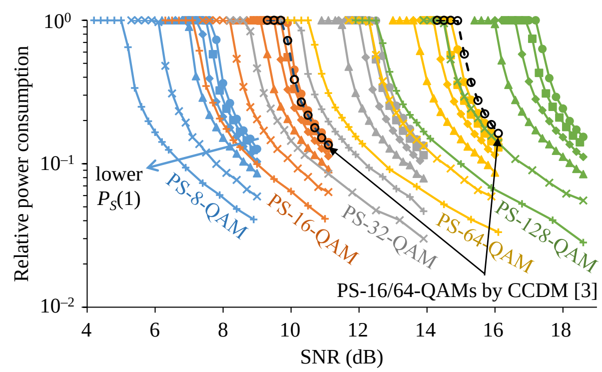


Fig. 5. Relative power consumption of the FEC decoding as a function of SNR for PS-QAM. Solid (black dashed) lines correspond to the proposed DM (CCDM).

5. Conclusions

We proposed the application of hierarchical DM to simultaneous source compression and probabilistic shaping, which is a kind of joint source–channel coding, with a suitable minimal-size two dimensional QAM constellation template. The compression feature varies the symbol entropy in the channel with time, depending on the source traffic. Simulation results showed several dB lower required SNR or reduced power consumption to about a tenth of a conventional scheme such as CCDM. Potential future works would include analysis of the impact of the variable symbol entropy and the development of power and SNR control methods in the systems.

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