Adaptive Coded Modulation Scheme for Free-Space Optical Communication

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Free space optical (FSO) communication techniques can provide long-distance high-speed links, at a lower cost. Therefore, they are considered as promising candidates for the backhauls of beyond-5G terrestrial and next-generation satellite communication systems [1]. Nevertheless, FSO signals are subject to time-variant atmospheric turbulence, which can cause severe degradation in the performance. One possible way to achieve efficient FSO communication is by the joint design of higher-order modulation schemes with error-correcting codes, usually referred to as coded modulation [2]. However, the design of efficient coded modulation systems is a challenging task. For instance, the distribution of the constellation symbols is not, in general, the capacity-achieving one, causing what is called the shaping gap [3].

Probabilistic shaping (PS) can decrease the difference between the transmission rate and Shannon's limit by optimizing the probabilities associated with different symbols in the constellation [4]. However, the majority of existing work considers only PS for optical fiber communication [4], [5].

For FSO with intensity modulation/direct detection (IM/DD), the signal constellation adheres to additional constraints compared to those adopted in fiber optical communications. In particular, the input distribution is subject to non-negative signaling and average optical power constraints. Tight lower and upper bounds on the capacity of intensity channels with average optical power constraint are derived in [6]–[8]. To the best of the authors' knowledge, efficient adaptive coded modulation schemes for M-ary pulse amplitude modulation (M-PAM) with fine granularity in FSO channels are still lacking in the literature.

In this work, we provide an adaptive coded modulation scheme with fine granularity to approach the capacity of FSO channels with IM/DD. The proposed encoder considers probabilistic shaping of a unipolar M-PAM constellation with a fixed-to-fixed length constant composition distribution matcher (CCDM), followed by efficient forward error correction (FEC) codes. An algorithm is proposed to determine the capacity-achieving input distribution for the coded modulation scheme over a wide range of signal-to-noise ratios (SNRs).

I. Signal Model

Let us consider n transmissions over a discrete-time FSO channel. The received signal at time instant i can be written as $Y_i = G\,X_i + W_i$, where W_i is a Gaussian noise with zero mean and variance σ^2, and G is a Gamma-Gamma random variable (r.v.) representing the fading due to the atmospheric turbulence. The channel input is X_i, which is a unipolar M-PAM signal with symbols $\mathbf{a} \triangleq [0, \Delta, \cdots, (M-1)\Delta]$, and Δ is the spacing between the levels. The vector $\mathbf{p} \triangleq [p_0, p_1, \cdots, p_{M-1}]$ represents the probabilities assigned to the constellation symbols.

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II. Proposed Coded modulation scheme

We propose an adaptive coded modulation scheme to increase the bandwidth efficiency of FSO communications by probabilistically shaping the input distribution, as shown in Fig. 1. First, we compute the capacity-achieving distribution of the proposed scheme, which permits the highest reliable communication rate for a given SNR. More precisely, we maximize the transmission rate, while satisfying both the power constraint and the reliability of the scheme by having the transmission rate less than achievable rate. The maximum achievable transmission rate can be found by solving the following optimization problem

$$\begin{aligned} \underset{\Delta, \mathbf{p} \text{ PDF}}{\text{maximize}} \quad & R(\mathbf{p}) \\ \text{subject to} \quad & c\,\mathbf{a}^T\,\mathbf{p} + (1-c)\Delta\frac{M-1}{2} \leq P \\ & R(\mathbf{p}) \leq R_{\text{SDT}}(g, \Delta, \mathbf{p}), \end{aligned} \tag{1}$$

where P is the average optical power limit, c is the FEC rate, g is the channel state information, $R(\mathbf{p})$ is the transmission rate, and $R_{\text{SDT}}(g, \Delta, \mathbf{p})$ is the mutual information between the input and the output of the proposed scheme (i.e., an achievable rate). The problem is not convex; however, it can be represented as a difference of convex functions, then efficiently solved by the convex-concave procedure.

Then, the CCDM transforms the uniformly distributed input bit string into unipolar M-PAM symbols with the targeted distribution. The CCDM has the advantage of being a fixed-to-fixed length scheme with low complexity. The rate of the CCDM converges to the entropy of the source, for an asymptotically large number of output symbols [9].

In order to achieve reliable communication with high spectrum efficiency close to the channel capacity, an FEC scheme should be employed. We opt for binary FEC encoders, as they have low complexity compared to non-binary methods. In this regard, the probabilistically shaped M-PAM signal is first mapped into a binary string. In this scheme, any systematic binary FEC encoder with the rate c and appropriate dimension can be employed.

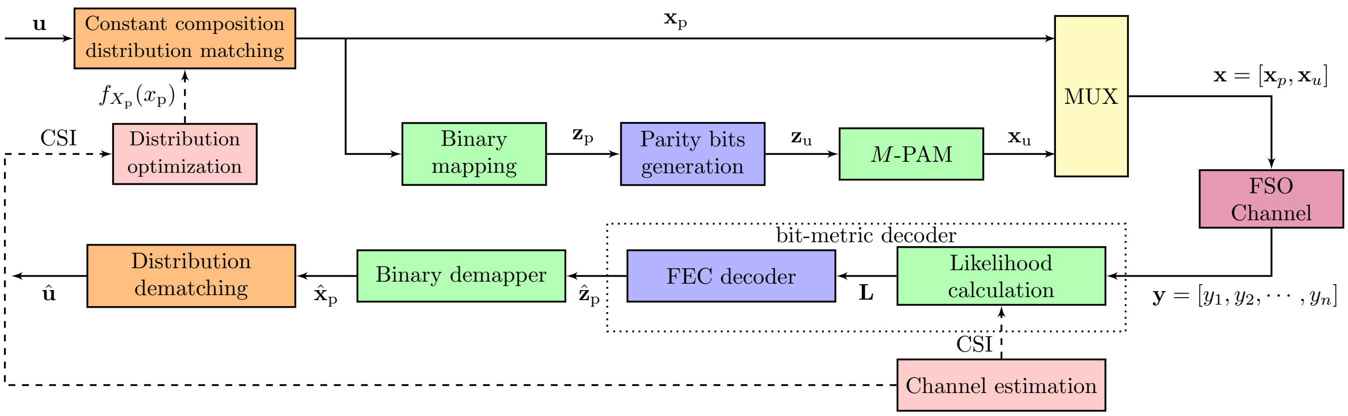

Fig. 1: The proposed probabilistic shaping scheme using unipolar M-PAM for FSO.

Although the signal at the FEC input is probabilistically shaped, the parity bits at its output tend to be uniformly distributed. This is attributed to the fact that each redundancy bits results from a modulo-2 sum of a large number of bits. These parity bits are mapped to the corresponding $(1-c)\,n$ M-PAM symbols, which are also uniformly distributed. Then, the parity symbols are multiplexed with the probabilistically shaped signal to form the codeword $\mathbf{x}$. Since the uniform distribution maximizes the source entropy (dense information representation), while the probabilistically shaped symbols have less amount of information (sparse). This scheme can be considered as a sparse-dense transmission (SDT) approach. In the following, we refer to the proposed scheme by sparse-dense with constant composition based coded modulation for FSO (SpaDCoM).

Regarding the decoder, a bit-metric decoder (BMD) can yield a rate close to the SDT capacity, while having lower complexity than symbol-metric decoder (SMD). The likelihood ratios for the bits are calculated and provided to the FEC decoder for soft decision-based estimation of the transmitted bits. Finally, the estimated bits are mapped into the corresponding symbols, and the distribution dematching estimates the original bits.

In Fig. 2, the transmission rate of the proposed SpaDCoM versus SNR is compared with the achievable rate of the uniform signaling and the capacity of 16-PAM. The optimal rate that maximizes the achievable rate for the SpaDCoM tends to use the highest FEC rate to approach the M-PAM capacity. On the other hand, the FEC rate for the uniform based scheme is selected such that the transmission rate is less than the achievable rate with uniform signaling. The suggested scheme operates within 1 dB from the M-PAM capacity and within 0.3 dB from the SDT capacity, at $R = 1.5$. Also, it outperforms the uniform signaling with more than 1 dB for $R = 1.5$, and up to 2.5 dB for $R = 0.5$, where the gap increases for lower transmission rates.

III. Conclusion

In this work, we propose a coded modulation scheme for FSO communication. The encoder is adaptive to the atmospheric turbulence-induced fading with arbitrary fine granularity. In particular, the signal constellation is probabilistically shaped by a low complexity fixed-to-fixed length distribution matcher to approach the capacity of FSO channels with IM/DD. The proposed method outperforms the uniform signaling based encoders. For instance, the suggested scheme operates within 0.3 dB from the capacity of unipolar M-PAM, and it outperforms the uniform signaling with 2.5 dB and 2 dB, for transmission rates of 0.5 and 1 bpcu, respectively.

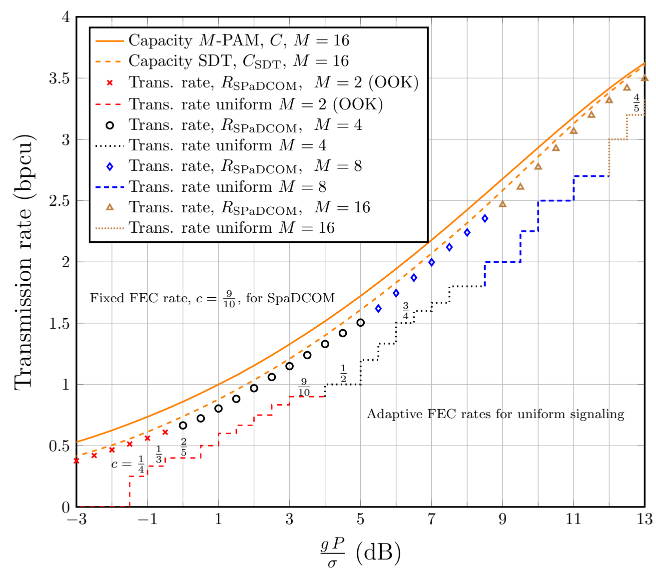

Fig. 2: The transmission rate vs SNR for the proposed SpaDCoM scheme, for various modulation orders $M \in \{2, 4, 8, 16\}$, along with the transmission rate of uniform signaling and the capacity of the 16-PAM as a benchmark.

References

[1] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M. -S. Alouini, "FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 218–224, Jan 2018.
[2] G. Ungerboeck, "Trellis-coded modulation with redundant signal sets part I: Introduction," *IEEE Commun. Mag.*, vol. 25, no. 2, pp. 5–11, 1987.
[3] G. Forney, R. Gallager, G. Lang, F. Longstaff, and S. Qureshi, "Efficient modulation for band-limited channels," *IEEE J. Sel. Areas Commun.*, vol. 2, no. 5, pp. 632–647, Sep. 1984.
[4] G. Böcherer, F. Steiner, and P. Schulte, "Bandwidth efficient and rate-matched low-density parity-check coded modulation," *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 4651–4665, Dec 2015.

[5] G. Böcherer, P. Schulte, and F. Steiner, "Probabilistic shaping and forward error correction for fiber-optic communication systems," *J. of Lightwave Technology*, vol. 37, no. 2, pp. 230–244, Jan 2019.

[6] A. Lapidoth, S. M. Moser, and M. A. Wigger, "On the capacity of free-space optical intensity channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 10, pp. 4449–4461, 2009.

[7] A.Farid and S. Hranilovic, "Capacity bounds for wireless optical intensity channels with Gaussian noise," *IEEE Trans. Inf. Theory*, vol. 56, no. 12, pp. 6066–6077, Dec 2010.

[8] A. Chaaban, J. Morvan, and M. -S. Alouini, "Free-space optical communications: Capacity bounds, approximations, and a new sphere-packing perspective," *IEEE Trans. Commun.*, vol. 64, no. 3, pp. 1176–1191, March 2016.

[9] P. Schulte and G. Böcherer, "Constant composition distribution matching," *IEEE Trans. Inf. Theory*, vol. 62, no. 1, pp. 430–434, Jan 2016.