Multidimensional modulation for next-generation transmission systems

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Abstract

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Multidimensional modulation for next-generation transmission systems

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ABSTRACT

Recent research in multidimensional modulation has shown great promise in long reach applications. In this work, we will investigate the origins of this gain, the different approaches to multidimensional constellation design, and different performance metrics for coded modulation. We will also discuss the reason that such coded modulation schemes seem to have limited application at shorter distances, and the potential for other coded modulation schemes in future transmission systems.

Keywords: Coded modulation, nonlinear transmission, coherent communications.

1. INTRODUCTION

While many of the modulation techniques digital signal processing (DSP) used in coherent optical transmission systems have been adapted from wireless systems,[1] there is increasingly interest in tailoring both modulation and DSP for the optical fiber channel, and the hardware constraints which result from the required levels of complexity and parallelism.[2] This was the motivation for the work of Karlsson and Agrell,[3,4] which reintroduced the concepts of optimizing modulation formats in more than two dimensions to the optical communications literature (after some early coherent work, e.g.[5]). Since this work, there has been a steady expansion of both modulation formats,[6,7] coded modulation techniques,[8–10] and other techniques which may be considered as multidimensional modulation – in particular, probabilistic shaping.[11,12]

In this paper, we will describe several design methodologies for multi-dimensional modulation formats. We consider a variety of performance metrics, including bit error rate (BER) and generalized mutual information (GMI).

2. MULTIDIMENSIONAL CODED-MODULATION COMMUNICATION SYSTEMS

A multidimensional coded-modulation system is shown in the schematic in Fig.1. A stream of data from the source is encoded by an outer encoder. The encoded symbol stream is then mapped to multidimensional symbols, on the optical carrier. This block may involve several sub-blocks in specific implementations, such as an inner encoder, followed by a bit-to-field mapping (such as a BPSK mapper), and then a mapping of BPSK symbols to multiple orthogonal field components and time slots. The multidimensional signal is then sent via the channel to the multidimensional de-mapper. The de-mapped data stream is then decoded by the outer decoder, with optional feedback to the multidimensional de-mapper (turbo-demodulation), before being sent to the sink. The de-mapper may output soft or hard decisions, and may be a maximum-likelihood de-mapper, or a numerical approximation with reduced complexity.[13]

3. MULTIDIMENSIONAL CONSTELLATION DESIGN

While there are a multitude of methodologies for designing a multidimensional modulation scheme, there are several methods which are particularly well explored. Sphere-packing formats are designed with the optimal arrangement of hyperspheres inside a larger hypersphere of the same dimension,[4] in order to maximize the minimum distance between hypersphere centroids. This is a well-explored mathematical problem, and several optimal solutions are known for particular numbers of dimensions and constellation points. These formats

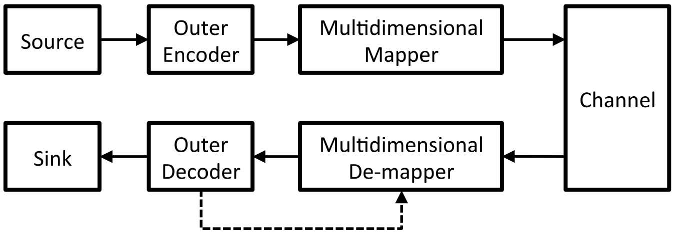


Figure 1. Schematic showing a generic multidimensional coded modulation system. The dashed line between the outer decoder and multidimensional de-mapper represents optional turbo-demodulation.

require an optimized bit-to-symbol mapping when the channel code used does not have the same cardinality as the modulation format. For sphere-packing formats, this is often not a significant problem, as the optimal mapping can be computed by brute force in cases with relatively low cardinality, such as those where optimal sphere-packings are known.

Sphere cutting formats are based on the cutting of a subset of points lying within the hypersphere on a lattice which is the optimal sphere-packing lattice in a given number of dimensions.[6, 14] Again, some lattices are proven to be optimal in certain numbers of dimensions. These formats also require an optimized bit-to-symbol mapping, which can be problematic in the case where the cardinality of the format is large, and brute force computation quickly becomes impossible. For example, the format based on the selection of 2^{12} points from the Leech lattice (which is known to be the optimal packing in 24 dimensions[15]) has a total number of labelings of $(2^{12}-1)!$, which (using Stirling's approximation) gives on the order of $10^{13,000}$ unique labelings. In cases where brute force labeling optimization is impossible, numerical techniques such as bit-flipping are often used,[16] although it is worth noting that these numerical methods cannot be guaranteed to reach a global optimum.

Perhaps the most popular method for designing modulation formats relies on the use of an inner block code,[6, 7, 17] with a separate mapper to map encoded bits to the optical field. These block coded solutions are particularly interesting, as they can provide codewords with optimal spacing in Hamming distance, while using a simple mapper to the optical field, which has few levels (thus reducing required hardware complexity).

3.1 AWGN optimized formats

Design of formats for performance in the presence of additive white Gaussian noise (AWGN) is useful for systems with high accumulated chromatic dispersion (CD).[18] In the uncoded case (which is of little practical interest in high capacity transmission systems), sphere-packing and sphere-cutting designs can provide good and, in some cases, optimal performance. This is due to their optimization of the minimum distance between constellation points.

When coding is used, the distribution of constellation distances, and the corresponding distribution of Hamming distances becomes increasingly important. In this case, we note that the attributes of block-coded formats become more desirable. While extended Hamming or extended Golay coded formats have proven useful at lower spectral efficiencies (using BPSK mapping per dimension), at higher spectral efficiencies, simple single parity check (SPC) coding is most commonly used.[19]

Due to the increasing use of low-rate soft-decision (SD) forward error correction (FEC) codes for high spectral efficiency, short-reach systems,[20] the usefulness of block-coded formats for such systems seems doubtful. This is due to the ability of square QAM formats with bit-interleaved coded modulation (BICM) to approach the uniform input distribution bound given an appropriate format and code rate.[21] However, utilizing constellation shaping to approach the Gaussian input distribution bound in this regime has become an increasingly important topic.[22]

3.2 Optical nonlinearity mitigating formats

When designing formats for use on nonlinear optical links, a gain can be demonstrated by using formats which minimize this optical nonlinearity. This is particularly prominent for links with low accumulated CD. In particular, polarization-managed formats (which seek to minimize the effect of cross-polarization modulation –

XPolM),[23] and formats with a constant modulus (which seek to minimize the effects of SPM and XPM)[24] have proven particularly successful. We note that this is a research problem with several good results, but few known performance bounds, although it has been posited that the use of coded modulation may enable systems which approach the nonlinear channel capacity.[25]

3.3 Performance metrics for modulation schemes

When designing multidimensional modulation schemes, it is of vital importance to use the appropriate performance metric for the type of coding system which will be employed.

Asymptotic power efficiency (APE) is a metric for the normalized minimum distance between the constellation points.[3] Due to its simplicity and ambivalence to bit-labeling, this metric is heavily used. While it is a good metric for the performance of uncoded communication in the presence of AWGN, this metric can be misleading for coded systems, as the impact of symbol errors may vary according to the Hamming distance between adjacent constellation points and/or the relative reliability of the symbols in the constellation.

Bit error rate (BER) is a good metric for the performance of hard-decision (HD) coded systems. While this metric is the most commonly used in the optical communications literature, it can be misleading for the use of SD-FEC,[21] which is used in current cutting edge systems.This is due to the fact that BER ignores the impact of correctly received and highly reliable symbols in SD-FEC decoders. That is, a symbol may not simply be correctly received or not, but it may be correctly received with high reliability, which will improve the decoder performance.

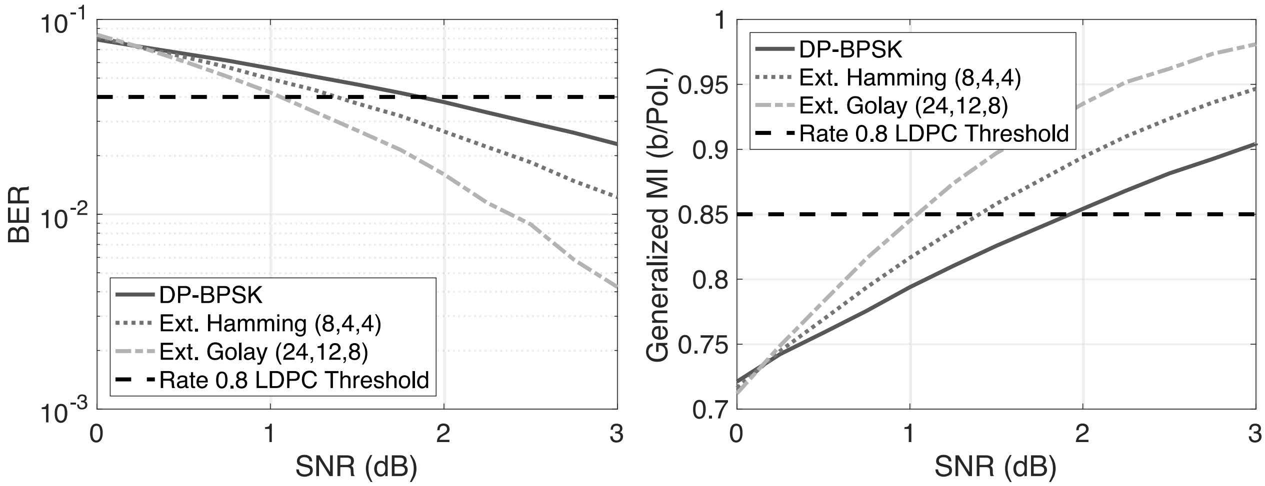
Mutual information (MI) is used to characterize the maximum amount of information that a received symbol sequence can carry, given the corresponding transmitted sequence.[21] While this metric is useful for the characterization of general coded modulation systems, the MI can only be achieved with either non-binary FEC (with cardinality equal to at least that of the modulation format), or when turbo-demodulation is used.

Generalized mutual information (GMI) measures the maximum amount of information that a received symbol sequence can carry, given the transmitted sequence, a bit-to-symbol mapping, and a de-mapping function.[21] This allows the characterization of systems which use BICM with binary SD-FEC. Since this is the most commonly-used FEC scheme in state-of-the-art transmission systems, we assert that this is the performance metric which of most interest to long-distance and high-capacity applications.

4. PERFORMANCE CHARACTERIZATION OF BLOCK-CODED MULTIDIMENSIONAL MODULATION FORMATS

In Fig.2, we show the performance of a pair of block-coded multidimensional modulation formats and compare them to dual-polarization BPSK (DP-BPSK), which is a common choice of modulation for long links with low SNR. The first of the two block codes shown is the (8,4,4) extended Hamming code, which has word length 8, information length 4, and minimum Hamming distance 4. This code is also known as the (8,4,4) biorthogonal code, and the (8,4,4) self-dual code, and has been investigated extensively.[6,7,23] The second code is the (24,12,8) extended Golay code, which has word length 24, information length 12, and minimum Hamming distance 8. While it has not been studied quite as widely as the (8,4,4) extended Hamming code, this modulation format has previously been experimentally demonstrated.[26]

We note from both Fig.2(a) and (b), that the performance of the multidimensional coded modulation improves with code length when the SNR is above a threshold of approximately 0.2 dB. This performance improvement increases with SNR, and will asymptotically reach the APE gain (6 dB for the extended Golay code, and 3 dB for the extended Hamming code). We compare the performance of the modulation formats with a rate 0.8 LDPC code with GMI threshold of 0.85 (similar to those already described in the literature[27]), and at a BER of 4×10^{-2} (which corresponds to a GMI of 0.85 for DP-BPSK modulation). The gain of the (8,4,4) code is 0.5 dB in SNR compared with DP-BPSK at a BER of 4×10^{-2}, and 0.5 dB in SNR when comparing performance at a GMI of 0.85. We also note that the gain of the (24,12,8) code compared with DP-BPSK is 0.8 dB when comparing at a fixed BER of 4×10^{-2}, while it is 0.9 dB when comparing at a fixed GMI of 0.85. While this difference is not so dramatic as those reported for dense QAM signals where the difference in reliability of the most and least significant bits is significant.



(a) (b)

Figure 2. Example of performance characterization of two multidimensional modulation formats, compared with a conventional format (DP-BPSK). Variation of BER with SNR is shown left in part (a), while variation of GMI with SNR is shown right in part (b).

5. CONCLUSIONS

We have summarized the current state of multidimensional modulation techniques, and described several methods for designing multidimensional modulation schemes. Different performance metrics were described, and compared. We have noted the increasing interest in constellation shaping and nonlinearity-mitigating modulation design. While many of the techniques for multidimensional modulation design are not new, the unique constraints of high-speed optical transmission systems are currently providing a new outlet for these methods. In contrast, the challenges of designing modulation which can mitigate optical nonlinearity are new unique and open. It is in this field that it seems the greatest gains may be realized.

REFERENCES

[1] Savory, S. J., “Digital coherent optical receivers: Algorithms and subsystems,” *IEEE Journal of Selected Topics in Quantum Electronics* **16**(5), 1164–1179 (2010).

[2] Koike-Akino, T., Kojima, K., Millar, D., Parsons, K., Yoshida, T., and Sugihara, T., “Pareto optimization of adaptive modulation and coding set in nonlinear fiber-optic systems,” *Journal of Lightwave Technology* (2016).

[3] Karlsson, M. and Agrell, E., “Which is the most power-efficient modulation format in optical links?,” *Optics express* **17**(13), 10814–10819 (2009).

[4] Agrell, E. and Karlsson, M., “Power-efficient modulation formats in coherent transmission systems,” *Journal of Lightwave Technology* **27**(22), 5115–5126 (2009).

[5] Betti, S., Curti, F., De Marchis, G., and Iannone, E., “Exploiting fibre optics transmission capacity: 4-quadrature multilevel signalling,” *Electronics Letters* **26**(14), 992–993 (1990).

[6] Millar, D. S., Koike-Akino, T., Arık, S. Ö., Kojima, K., Parsons, K., Yoshida, T., and Sugihara, T., “High-dimensional modulation for coherent optical communications systems,” *Optics express* **22**(7), 8798–8812 (2014).

[7] Eriksson, T. A., Johannisson, P., Puttnam, B. J., Agrell, E., Andrekson, P. A., and Karlsson, M., “K-over-L multidimensional position modulation,” *Lightwave Technology, Journal of* **32**(12), 2254–2262 (2014).

[8] Djordjevic, I. B., “On the irregular nonbinary QC-LDPC-coded hybrid multidimensional OSCD-modulation enabling beyond 100 Tb/s optical transport,” *Journal of Lightwave Technology* **31**(16), 2969–2975 (2013).

[9] Lotz, T., Liu, X., Chandrasekhar, S., Winzer, P., Haunstein, H., Randel, S., Corteselli, S., Zhu, B., and Peckham, D., "Coded PDM-OFDM transmission with shaped 256-iterative-polar-modulation achieving 11.15-b/s/Hz intrachannel spectral efficiency and 800-km reach," *Journal of Lightwave Technology* **31**(4), 538–545 (2013).

[10] Cai, J.-X., Batshon, H. G., Zhang, H., Mazurczyk, M., Sinkin, O., Foursa, D., and Pilipetskii, A., "Transmission performance of coded modulation formats in a wide range of spectral efficiencies," in [*Optical Fiber Communication Conference*], M2C–3, Optical Society of America (2014).

[11] Buchali, F., Steiner, F., Böcherer, G., Schmalen, L., Schulte, P., and Idler, W., "Rate adaptation and reach increase by probabilistically shaped 64-QAM: An experimental demonstration," *Journal of Lightwave Technology* **34**(7), 1599–1609 (2016).

[12] Fehenberger, T., Alvarado, A., Böcherer, G., and Hanik, N., "On probabilistic shaping of quadrature amplitude modulation for the nonlinear fiber channel," *Journal of Lightwave Technology* **34**(21), 5063–5073 (2016).

[13] Yoshida, T., Matsuda, K., Kojima, K., Miura, H., Dohi, K., Pajovic, M., Koike-Akino, T., Millar, D. S., Parsons, K., and Sugihara, T., "Hardware-efficient precise and flexible soft-demapping for multi-dimensional complementary APSK signals," in [*ECOC 2016; 42nd European Conference on Optical Communication; Proceedings of*], Th.2.P2.SC3.27, VDE (2016).

[14] Koike-Akino, T. and Tarokh, V., "Sphere packing optimization and EXIT chart analysis for multi-dimensional QAM signaling," in [*Communications, 2009. ICC'09. IEEE International Conference on*], IEEE (2009).

[15] Cohn, H., Kumar, A., Miller, S. D., Radchenko, D., and Viazovska, M., "The sphere packing problem in dimension 24," *arXiv preprint arXiv:1603.06518* (2016).

[16] Hager, C., Amat, A. G. I., Alvarado, A., Brannstrom, F., and Agrell, E., "Optimized bit mappings for spatially coupled LDPC codes over parallel binary erasure channels," in [*Communications (ICC), 2014 IEEE International Conference on*], 2064–2069, IEEE (2014).

[17] Karlsson, M. and Agrell, E., "Multidimensional modulation and coding in optical transport," *Journal of Lightwave Technology* (2016).

[18] Poggiolini, P., "The GN model of non-linear propagation in uncompensated coherent optical systems," *Journal of Lightwave Technology* **30**(24), 3857–3879 (2012).

[19] Puttnam, B., Eriksson, T., Mendinueta, J.-M. D., Luís, R., Awaji, Y., Wada, N., Karlsson, M., and Agrell, E., "Modulation formats for multi-core fiber transmission," *Optics express* **22**(26), 32457–32469 (2014).

[20] Millar, D. S., Maher, R., Lavery, D., Koike-Akino, T., Pajovic, M., Alvarado, A., Paskov, M., Kojima, K., Parsons, K., Thomsen, B. C., et al., "Design of a 1 tb/s superchannel coherent receiver," *Journal of Lightwave Technology* **34**(6), 1453–1463 (2016).

[21] Alvarado, A., Agrell, E., Lavery, D., Maher, R., and Bayvel, P., "Replacing the soft-decision FEC limit paradigm in the design of optical communication systems," *Journal of Lightwave Technology* **34**(2), 707–721 (2016).

[22] Koike-Akino, T., Millar, D. S., Parsons, K., and Kojima, K., "GMI-maximizing constellation design with grassmann projection for parametric shaping," in [*Optical Fiber Communications Conference and Exhibition (OFC), 2016*], M2A.4, IEEE (2016).

[23] Shiner, A., Reimer, M., Borowiec, A., Gharan, S. O., Gaudette, J., Mehta, P., Charlton, D., Roberts, K., and O'Sullivan, M., "Demonstration of an 8-dimensional modulation format with reduced inter-channel nonlinearities in a polarization multiplexed coherent system," *Optics express* **22**(17), 20366–20374 (2014).

[24] Kojima, K., Yoshida, T., Koike-Akino, T., Millar, D. S., Parsons, K., and Arlunno, V., "5 and 7 bit/symbol 4d modulation formats based on 2A8PSK," in [*ECOC 2016; 42nd European Conference on Optical Communication; Proceedings of*], W.2.D.1, VDE (2016).

[25] Agrell, E. and Karlsson, M., "Satellite constellations: Towards the nonlinear channel capacity," in [*Photonics Conference (IPC), 2012 IEEE*], 316–317, IEEE (2012).

[26] Millar, D. S., Koike-Akino, T., Maher, R., Lavery, D., Paskov, M., Kojima, K., Parsons, K., Thomsen, B. C., Savory, S. J., and Bayvel, P., "Experimental demonstration of 24-dimensional extended golay coded modulation with LDPC," in [*Optical Fiber Communications Conference and Exhibition (OFC), 2014*], M3A.5, IEEE (2014).

[27] Sugihara, K., Miyata, Y., Sugihara, T., Kubo, K., Yoshida, H., Matsumoto, W., and Mizuochi, T., "A spatially-coupled type LDPC code with an NCG of 12 dB for optical transmission beyond 100 Gb/s," in [*Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), 2013*], OM2B.4, IEEE (2013).