Polar Coding for Multilevel Shaped Constellations

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Abstract

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OCIS codes: (060.4510) Optical communications, (060.1660) Coherent communications, (060.4080) Modulation.

1. Introduction

We investigate polar codes [1–4] as viable candidates of forward error correction (FEC) codes for future optical communications. Polar codes have received significant amount of attention in the coding theory community since Arıkan proved their ability to achieve capacity over any arbitrary discrete-input memoryless channels. More recently, decoding performance was significantly improved by introducing successive-cancellation list (SCL) decoding plus cyclic redundancy check (CRC). Consequently, polar codes are now able to outperform state-of-the-art low-density parity-check (LDPC) codes, in particular at short block lengths. Due to the excellent performance and simple decoding algorithm, polar codes were chosen for the fifth-generation (5G) wireless standard. However, the conventional polar code construction assumes memoryless identical channel reliability, which is not valid when we use high-order quadrature-amplitude modulation (QAM) having different reliability across the most to least significant bit-planes. In this paper, we present our research activities to design polar-coded multilevel modulation. We also discuss constellation shaping, complexity/latency reduction with irregular polarization, and highly parallel decoding.

2. Advanced Techniques for Polar Coding

Polar codes for high-order QAMs were discussed in [3] for bit-interleaved coded modulation (BICM) and in [4] for multilevel coded modulation (MLC). Although MLC can outperform BICM in principle, BICM is particularly of interest in some practical systems because BICM does not require code rate controls per bit-planes, successive decoding, and block length slicing. Since polar codes exploit so-called channel polarization phenomenon, careful interleaver design which properly maps the coded bits to modulation bit-planes for BICM is of great importance not to destruct the polarization phenomenon. In [5], we optimized an interleaver parameter of hardware-efficient quadratic polynomial permutation (QPP), achieving greater than 0.5 dB gain against random interleaving. It was extended to orthogonal frequency-division multiplexing (OFDM) in [6], where we further introduced constellation shaping based on super-Gaussian geometry to adjust Gaussianity in a seamless manner. The proposed shaping offers additional 0.4 dB gain for polar-coded 256QAM. In [7], we further proposed joint optimization of frozen bit selection and interleaver design via extrinsic information transfer (EXIT) evolution, showing improved rate of channel polarization.

It is well-known that irregular LDPC codes having well-designed degree distribution can perform better than regular counterparts. Motivated by the fact, in [7–9] we proposed a new code construction method for irregular polar codes, whose polarization kernels are irregularly pruned to drastically reduce the computational complexity and decoding latency while achieving better performance. Since pruned polarization units do not need any computation for both encoding and decoding, we can reduce the computational complexity. In addition, the decoding latency can be also reduced by carefully choosing the set of inactive polarization units to enable partially parallel computations. The proposed irregular polar codes showed slightly better performance than regular ones while reducing decoding complexity by at least 30% and decoding latency by 80%. Moreover, in [10] we developed turbo product codes based on irregular polar codes to enable highly parallel SCL decoding, realizing more than 256-times faster decoding throughput.

3. Polar Coding Performance for Shaped High-Order Modulation

In this paper, we analyze the performance of irregular polar codes [8] with optimized QPP interleaver [5] for high-order QAM formats shaped by super-Gaussian geometry [6]. The super-Gaussian shaping maps constellation points

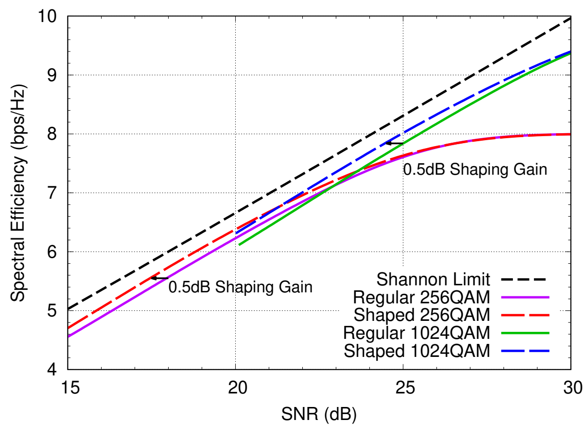

Fig. 1: BICM bound of super-Gaussian-shaped QAMs.

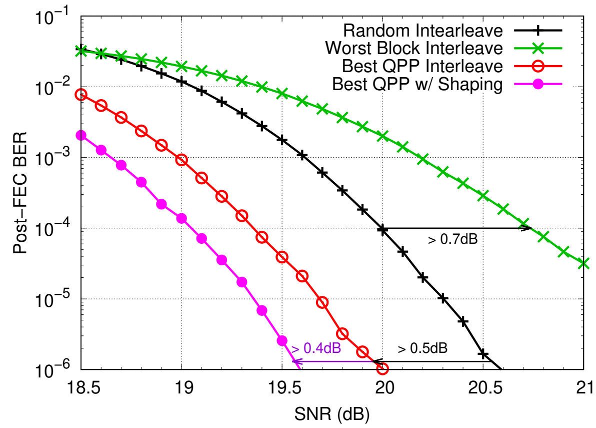

Fig. 2: Bit-interleaved polar-coded 256QAM.

distributed as $f(x) \propto \exp(-(\alpha|x|)^{2\gamma})$, where α and β are normalization factor and Gaussianity control factor, respectively. We show the shaping gain in Fig. 1 which plots the achievable spectral efficiency in terms of generalized mutual information (GMI) of 256 and 1024QAMs with and without super-Gaussian shaping. The optimal γ was 2.1 and 1.8 for 256 and 1024QAM, respectively. We can observe that the super-Gaussian shaping offers up to 0.5 dB gain.

The benefit of interleaver design for 256QAM is shown in Fig. 2, where the SCL decoder performance of (1024, 828) irregular polar coding (with CRC-8 and list size of 32) is present. More than 1 dB difference is seen between good and bad interleaving methods because polarization phenomenon is greatly affected by bit mapping. The QPP interleaver was originally used for turbo coding in wireless standards. The n-th coded bit is interleaved by QPP(f_0, f_1, f_2) as follows: $\pi(n) = (f_0 + f_1 n + f_2 n^2) \bmod N$, where f_0, f_1, and f_2 are interleaver coefficients to be optimized under the constraints that f_1 must be co-prime to N and f_2 must contain all prime factors of N. The optimized parameter was QPP$(0, 7, 0)$. By using constellation shaping, we can further improve performance by additional 0.4 dB. In addition, the proposed irregular polar codes can reduce the decoding complexity and latency by approximately 25% and 60%, respectively, without sacrificing any performance penalty.

4. Conclusions

In this paper, we introduced recent proposals for advanced polar codes, which can realize high-throughput, high-performance, low-power, and low-latency optical communications. We gave an overview of frozen bit selection, interleaver design, super-Gaussian constellation shaping, irregular kernel pruning, and parallelizable architecture. In particular, we focused on bit-interleaved polar-coded modulation design for geometrically-shaped high-order constellations. We note that the concept of irregular polar codes has a lot of rooms to investigate by considering various different ways to introduce irregularity not only by pruning.

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