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Polar Lattices for Next-Generation Wireless Communications with Application to Cyber Ranges

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Extended Abstract

5G is the coming fifth-generation wireless broadband technology which will provide much better speeds, coverage, capacity and reliability than the current 4G systems. It is proposed to operate at 6 GHz band or millimeter waves and is set to provide peak data rates of up to 10 Gbps with 100 Mbps at cell edge. Commonly proposed cases for 5G networks are eMBB (Enhanced Mobile Broadband), Massive machine type communication (mMTC) and URLLC (Ultra Reliable and Low Latency Communications). While URLLC and nMTC are latency sensitive and need high reliabilty, eMBB supports a various ranges of Internet access with high data rates to enable huge media applications and real entertainment.

Recently, there is a lot of interest for the application of polar codes for next generation wireless communication networks due to its advantage compared to other state-of-the-art channel codes like turbo codes and LDPC codes. One reason is they lack a mathematical proof of capacity-achieving properties and partly reveal several drawbacks for very high speed wireless communications. Turbo codes are currently used for 3G/4G networks but they have several disadvantages such as consuming high energy per bit, having only a narrow range of good code rates and having a high complexity when the code length is larger. LDPC codes demonstrate very good performance at large code length with acceptable complexity but are not actually good at low code length. However polar codes with the proposed decoder can solve this problem efficiently. Polar codes, which were proposed by Arikan, are considered to be one of the major breakthroughs in coding theory for recent years. They are thus a promising candidate for the next generation wireless communication such as 5G cellular systems.

In this thesis, we propose a basic scheme for using polar codes in 5G

systems especially for small and moderate code lengths such as 64, 128, 256. For example, the simulation results show that the polar codes for short length of 128 with successive cancellation list (SCL) decoding outperforms the turbo codes at all rates of 1/3, 1/2 and 2/3. In addition, the polar codes length of 1024 with SCL decoding and CRC achieve even better performance than LDPC codes in equal conditions. We then analyze the polar codes performance under Rayleigh fading and propose to apply the SCL decoding and the suitable CRC sequence as the outer channel codes to overcome the negative effect of fading channels and get SNR gain. The selection of CRC bit length must be traded off with the code length because it causes the increase in bits redundancy for moderate code length. For instance, 2.5 dB gain is obtained for polar codes 1024 with rates of 0.5 under Rayleigh fading when using our proposed design.

Lattices and *lattice codes* has received the increasingly significant attention in applications to wireless communications from the research community. The advantage of a lattices based system is that it is able to merge the channel coding and the modulation as one process. It is necessary to separate the difference between lattices and lattice codes. In practice, only a finite set of points of a lattice Λ can be used as a signal constellation in a communication system. This set consists of those points of Λ that are contained in a bounded shaping region $\mathcal{S}$, and is known as the lattice code $\mathcal{C}(\Lambda, \mathcal{S})$. Since a *lattice* has infinite number of points, a *lattice code* is generated by applying a *power constraint* to an infinite lattice. This thesis *mainly concentrates* on transmitting lattices points without power constraint over AWGN channel but this is an importantly preceding step for the further work on lattice codes.

There are various techniques that construct lattices from finite-field codes. Lattice Construction maps symbols from a finite field code to lattice points. There exists several kinds of construction including Constructions A, B, C, D, D' and E. Meanwhile, the construction A was considered as a simple version one. Construction D is a generalization of Construction A. While Construction A uses a single code $\mathcal{C}_0$, Construction D uses a sequence of a nested binary codes: $\mathcal{C}_0 \subseteq \mathcal{C}_1 \subseteq ... \subseteq \mathcal{C}_{a-1}$. Due to the huge recent interest in the Construction D, this research thus mainly focuses on the Construction D with application to the lattices from polar codes.

Polar codes demonstrate good performance, and also have a nice nested property that are suitable for constructing lattices. We therefore propose lattices constructed from polar codes called as *polar lattices* by construction

D with modified multi-level decoding for Code formula decoding, instead of subtracting the estimated binarycodeword $\hat{\mathbf{c}}_i$, Construction D decoding subtracts integer vector $\hat{\mathbf{x}}_i$. In Yan and Cong Ling's study in 2012, the authors firstly proposed polar lattices designed by Barnes-Wall rule, but they did not mention how to investigate and select the code rate that achieves best polar lattices performance. We therefore propose to choose the code rates of polar codes at each level following the capacity rule that achieve the better performance. The simulation results show that polar lattices constructed by proposed code rate selection outperforms the previous polar lattices by the Barnes-Wall (BW) rule. For example, 2.5 dB gain is obtained at 10^{-3} of word error rate (WER) when we apply new approach instead of choosing the BW rule for polar lattices. The analysis is conducted for polar lattices in terms of unconstrained power over AWGN channel.

Various decoders have been used for lattices, where the sphere decoding algorithm is a maximum likelihood lattice decoding approach. It searches for lattice points within a fixed radius of the received signal but cost highest complexity. Inspired by syndrome decoding for finite-field codes, the lattice syndrome decoder at-tempts to find an estimated codeword closest to a received sequence. Syndrome decoding is based on storing error vectors in a lookup table, however some modifications are needed so lattice syndrome decoding can handle soft-input vectors. Four lattice syndrome decoding algorithms are presented, progressively solving a shortcoming of the previous one. the extension part of this thesis is an effort to propose the lattice syndrome decoding that is near-optimal decoding method for small dimensions and is relatively potential to apply to the MIMO systems.

In this thesis, the advantages of polar codes have been discussed and shown numerically that can be applied for 5G systems. However, the simulation results demonstrated only a low order of modulation scheme. In order to adapt to other advanced waveform methods, a higher constellation such as 64-QAM or 128-QAM should be considered.

Another interesting topic is the Gaussian shaping technique for polar lattices for the power-constrained AWGN channel. This is based on source polarization. In the further research, we will be able to achieve the capacity $1/2 \log(1 + \text{ SNR})$ with low-complexity multistage successive cancellation (SC) decoding for any given signal-to-noise ratio (SNR). In order to achieve this, we should investigate various shaping schemes for polar lattices.