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論　　文　　題　　目	Construction and Decoding of Complex Low Density Lattice Codes
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論文の内容の要旨

Coded modulation increases the spectral efficiency of wireless communication systems. Lattice codes are elegant and powerful structures for coded modulation that not only can achieve the capacity of the additive white Gaussian noise (AWGN) channel, but also are a key ingredient to many multi-terminal schemes that exploit linearity properties. There is an always-increasing demand for increased spectrum efficiency, massive connectivity and higher data rates; in post-5G or 6G wireless networks, lattice codes are a potential candidate to achieve these goals.

Low-density lattice codes (LDLC) defined over the real numbers is one type of lattice codes which show the decoded efficiently in high-dimensional Euclidean space, and error free decoding is possible within 0.6 dB of the unconstrained power channel capacity. These real-valued LDLC were extended to the complex numbers. Such complex low-density lattice codes (CLDLC) provide several advantages for future wireless network and also outperforms real LDLC. However, belief propagation (BP) decoding of CLDLC confronts the same issue as real LDLC, that an infinite Gaussian mixture must be approximated for the decoder implementation.

This dissertation provides three contributions for complex low-density lattice codes (CLDLC). First, a decoding algorithm for CLDLC using a likelihood-based reliability function is used to determine the number of complex Gaussian functions at the variable node. This allows each message to be approximated by a variable number of Gaussians depending upon its reliability. An upper bound on the Kullback-Leibler (KL) divergence of the approximation is formed to find selection thresholds via linear regression. Second, a construction of complex low-density lattice codes (CLDLC) using Eisenstein integers is given. Third, a generalized CLDLC Latin square construction and a corresponding condition for convergence of variances under belief propagation (BP) decoding is given. The proposed CLDLC decoding algorithm has higher performance and lower complexity compared to existing algorithms. When the reliability-based algorithm is applied to Eisenstein integer CLDLC decoding, the complexity is reduced to $O(n{\cdot}t{\cdot}1.35^{d-1})$ at volume-to-noise ratio of 6 dB, for lattice dimension n, with degree d inverse generator matrix and t

decoding iterations. Decoding CLDLC using Eisenstein integers has lower complexity than CLDLC using Gaussian integers when $n \geqslant 49$.

In addition, this dissertation has a contribution on low-density parity-check code (LDPC) decoders for NAND flash memory. The data read system for NAND flash memory can be modeled by a discrete memoryless channel (DMC) with unknown channel transition probabilities. However, LDPC decoders need a channel estimate, and incorrect channel estimation degrades the performance of LDPC decoder. This abstract proposes using the expectation maximization (EM) algorithm to estimate channel transition probabilities, needed to compute log-likelihood ratios (LLRs) for the LDPC decoders. At word-error rate 10^{-5}, the performance of the EM system was only 0.02 dB loss compared to the system that knows the channel exactly.

Keywords: Complex low-density lattice codes, Belief propagation decoder, Eisenstein integers, Low-density parity-check codes, NAND flash memory.

論文審査の結果の要旨

This dissertation is a significant contribution to the development of wireless communication systems by showing that lattices are a feasible alternative to existing modulation methods, while providing higher coding gain and being compatible with multiuser communications. The dissertation shows that low-density lattice codes are highly suitable for wireless communications because complex-valued lattices use precisely the same algebra as the standard communications channel. A major challenge of using lattices is their high decoding complexity. Her methods reduce the complexity of decoding by a novel threshold selection method, thoroughly investigated in this dissertation by considering real-valued lattices as well as Gaussian integer and Eisenstein integer complex lattices. In addition, this dissertation proposed LDLC lattices based on Eisenstein integers, and demonstrated that this new construction has both lower error rates and lower decoding complexity than other LDLC constructions. The analytical contributions include a new bound on the Kullback-Lieber (KL) divergence between Gaussian mixtures, the development of which was motivated by the need to efficiently make a threshold decision during decoding while avoiding expensive KL divergence computations. A new condition on the convergence of belief-propagation decoding is given, extending the existing convergence condition from regular to more general irregular constructions; this will enable new designs of LDLC lattices, and with the goal of bringing their performance closer to the channel capacity. The dissertation represents a comprehensive study, particularly on algorithms for decoding complex-valued low-density lattice codes.

The committee recognized this dissertation's novelty, contribution to the research community, and its advancement of wireless research. The committee agrees that this is an excellent dissertation, and the committee approves awarding the doctoral degree to Warangrat Wiriya.