様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　５ 年　 ９ 月 ２１ 日現在

機関番号：１３３０２
研究種目：基盤研究(B)（一般）
研究期間：2019～2022
課題番号：１９Ｈ０２１３７

研究課題名（和文）Lattice Codes for Gaussian Wireless Networks Beyond 5G

研究課題名（英文）Lattice Codes for Gaussian Wireless Networks Beyond 5G

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交付決定額（研究期間全体）：（直接経費）　　11,800,000円

研究成果の概要（和文）：新しい格子符号を開発し、無線通信ネットワークへの適合性を評価した。(1)高い符号化利得(2)既知の中で最高の1.25dBのシェーピング利得(3)効率的なシェーピングアルゴリズムを持つLDPC符号に基づく実用的な新しい格子符号を設計した。我々は、最もよく知られたBCH格子符号に近い誤り率を持ちながら、より低い復号複雑度を持つ極符号格子を128次元で設計した。 格子に対するretry復号の概念を導入し、境界を開発することにより、0.5dBの誤り率改善の可能性を示した。整数強制MIMOにおいて、直交プリコーディングが従来のユニタリープリコーディングよりも低い誤り率を与えることを示した。

研究成果の学術的意義や社会的意義
現在、社会は広く無線通信に依存している。ワイヤレス・ネットワークのさらなる改善を達成するために、情報理論に基づく格子ベースの結果は非常に有望であるが、無限次元格子を前提としていた。本研究は、有限長の格子符号を開発することにより、「理論」を「実践」に移す重要なステップである。本研究で開発した格子は、研究者や産業界が実用的なシステムを設計するために利用することができる。

研究成果の概要（英文）：We developed new lattice codes and evaluated their suitability for wireless communication networks. We designed practical new lattice codes based on LDPC codes with (1) high coding gain (2) highest known shaping gain of 1.25 dB (3) efficient shaping algorithm. We designed polar code lattices which have error rates close to best-known BCH lattice codes, but with much lower decoding complexity, in dimension 128. The concept of retry decoding for lattices was introduced, and showed a possible error-rate improvement of 0.5 dB by developing a mathematical bound. The error rates and efficiency of complex LDLC lattices were improved using Eisenstein integers. For integer-forcing MIMO, we showed that orthogonal precoding gives lower error rates than conventional unitary precoding. Sparse regression codes with irregular clipping achieves a 2.2 dB improvement over regular clipping.

研究分野： Information theory

キーワード： 情報理論　符号理論　格子　無線通信

１．研究開始当初の背景

There is an always-increasing demand for increased spectral efficiency and massive connectivity which cannot be satisfied by 5G mobile broadband. "Wireless networks beyond 5G" means devices and relays in complex networks must cooperate to fully exploit spectrum potential. Beyond 5G includes the Internet of Things (IoT), particularly the new category of reliable low-latency communications needed for automated vehicles, industrial automation and unmanned aerial vehicles. Most devices are battery-powered and must transmit and receive efficiently.

Recently, information theory has provided remarkable new insights into the theoretical limits of cooperative communications. Lattice codes were shown to achieve the point-to-point Gaussian channel capacity, and lattices can achieve the capacity of certain Gaussian networks, or nearly so. Lattices codes are essential for compute-forward schemes, which provide high throughput on multiuser wireless communications.

２．研究の目的

The research goal is the development of practical lattices for reliable communication, and their application to wireless networks of networked wireless devices. Lattices are codes defined on the real numbers, which differs from error-correcting codes based on finite fields. This work concentrates on the design of finite-length lattices, which differs from recent work on asymptotically long lattices. This work aims to support practical approaches to compute-and-forward, a recent theoretical technique to improve spectrum efficiency in Gaussian wireless networks.

３．研究の方法

The research method consists of the design of lattices and lattice codes, mathematical statements and their proofs, development of decoding algorithms and their software implementation. By separating into the these parts, we can deal with the problems systematically.

４．研究成果

The research results are separated into four work packages WP1–WP4 and results are described for each one.

(1) WP1 Lattice Codes for IoT

Real-time control applications require low-latency codes and IoT applications require high bandwidth efficiency. We designed a new lattice code with short block length and high coding rate which achieves this goal, called polar code lattices. We overcame the challenge of selecting the component code rates first by using extensive numerical simulations, and then by optimizing the design semi-analytically use the density evolution method.

The new dimension $n = 128$ polar code lattice has decoding complexity significantly lower than the best-known competing BCH code lattice. At same time, the new lattice code has error-rate performance within 0.2 dB of the BCH code lattice code, as shown in Fig. 1. As a result, the new lattice is a promising candidate for IoT applications [C8].

To minimize latency in real-time control systems, one strategy is to re-attempt decoding rather than requesting retransmission. To achieve this goal, we developed the concept of a self-checking lattice code. We developed a bound on the performance gain by assuming the existence of a genie-aided receiver which can determine if re-attempt decoding is needed. For the point-to-point channel, an analytic expression predicts that approximately 0.5 dB gain is possible; to construct this bound, the Voronoi region was approximated as a sphere, see Fig. 2. A practical code based on the E8 lattice achieved 0.1 dB gain [C1][C2].

(2) WP2: Network Lattice Codes

A. High Shaping Gain Lattice Code

We discovered and solved an important lattice coding problem. To be used in a practical wireless network, lattice codes must satisfy several requirements which enforce additional theoretical restrictions on the construction. Amongst these is finding a lattice code with (1) high coding gain (2) high shaping gain (3) efficient shaping algorithm.

We designed a new lattice code achieving these goals. (1) To achieve high coding gain, we used quasi-cyclic low-density parity-check codes. Because the coding lattice must satisfy a number of design

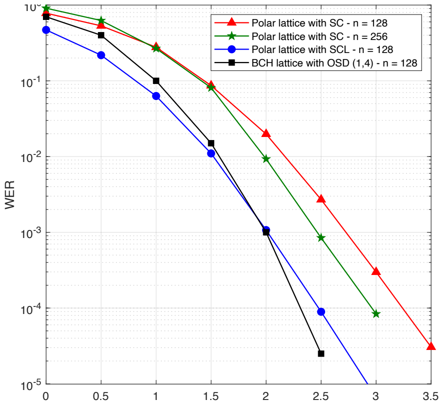

Figure 1: Proposed polar lattice code has performance very close to the existing BCH code; “list” decoding is used. Also shown is the same code with “successive cancellation” decoding, which has significantly lower complexity, but worse error rate [C8].

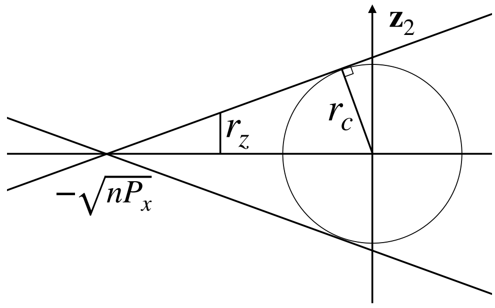

Figure 2: The covering sphere is used to approximate the Voronoi region of a lattice. An upper bound on the probability of decoding error is formed by integrating over the Gaussian noise in the cone formed by this sphere.

requirements, we used an innovative binary integer programming approach to design the parity-check matrix. In addition, quasi-cyclic LDPC codes are widely used in practice, making lattices appealing for practical implementation. [C9]

(2) For shaping to reduce transmit power, lattices based on convolutional codes have good shaping gain for modest complexity. However, there has been limited investigation of the best convolutional codes for shaping. We performed extensive investigation, and provided the first study of rate 1/3 convolutional codes which give the best-known shaping gain. In addition, we found various rate 1/2 convolutional codes as well. These are shown in Table 1.

(3) We showed that rate 1/3 convolutional codes have a better complexity/performance tradeoff than rate 1/2 convolutional codes. This was surprising because rate 1/2 convolution codes are more widely used, but can be explained because rate 1/3 codes have lower complexity per trellis section.

In summary, our construction has the highest-known shaping gain of 1.25 dB of any practical construction. We produced a new lattice code construction, using LDPC codes for coding gain, convolutional codes for shaping gain, and reduced complexity using rate 1/3 convolutional codes. The proposed lattices achieve all three goals (1), (2) and (3) to operate at lower SNR than existing modulation methods; they are also highly practical, making them a promising candidate for future wireless communication systems [J3].

B. Lattices for Complex-Valued Channels

We proposed new complex-valued low-density lattice code (LDLC) and a corresponding decoding algorithm. Coded modulation used in wireless communications systems is naturally complex, and thus complex-valued LDLCs are highly appropriate.

We proposed an innovative new LDLC lattice based on Eisenstein integers rather than the conventional Gaussian integers. The key insight is that the tighter packing of the Eisenstein integers lowers complexity of decoding by reducing the number of Gaussian messages needed for low error rates. Complex low density lattice codes (LDLC) have lower error rates than real-valued LDLCs, when the dimension $n \leq 500$, as shown in Fig. 3. The second novelty is an algorithm that adaptively selects the number of Gaussians based on a reliability metric. This reliability-based algorithm lowers complexity by using the smallest number of Gaussians needed for low error rates [C5].

(3) WP3: Simple Networks

Compute-and-forward techniques significantly improve spectrum utilization in Gaussian networks by allowing sources to transmit simultaneously. Lattices are required in order to form linear combinations of messages, as well as providing reliability.

Compute-forward using multiple antennas at both the transmitter and receiving is called integer-forcing multiple-input multiple-output (IF-MIMO). IF-MIMO aims to replace high complexity MIMO detection with lower complexity lattice decoding, but faces the challenge of precoder design.

To overcome this challenge, we developed an efficient algorithm based on steepest gradient that exploits the geometrical properties of orthogonal matrices as a Lie group. Using this algorithm, we showed that orthogonal precoding outperforms unitary precoding in terms of achievable rate, outage probability, and

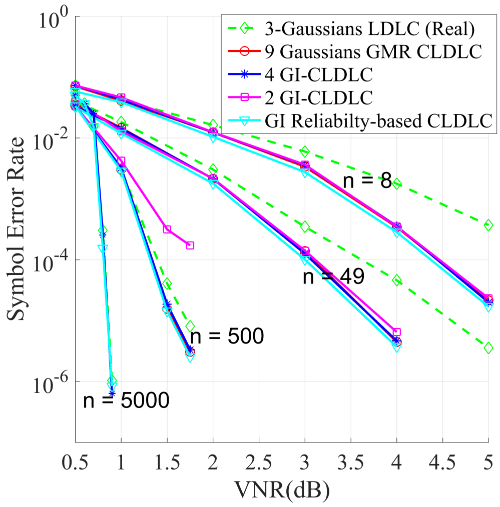

Figure 3: Complex low density lattice codes (LDLC) have lower error rates than real-valued LDLCs, when the dimension $n \leq 500$.

Table 1: Convolutional codes which give the best-known shaping gain for various memory orders *m*. (Octal number convention: $D^3 + D + 1$ is represented by 13)

Memory *m*	Rate [Code]	Shaping gain
2	1/2 [7,5]	0.9734 dB
3	1/2 [17, 13]	1.0622 dB
4	1/2 [31,23]	1.1233 dB
5	1/2 [75,57]	1.1814 dB
6	1/2 [165,127]	1.2251 dB
7	1/2 [357,251]	1.2574 dB
2	1/3 [7,6,5]	0.9055 dB
3	1/3 [17,15,13]	1.0673 dB
4	1/3 [37,33,25]	1.1321 dB
5	1/3 [73, 57, 31]	1.1808 dB

error rate. Fig. 4 shows the proposed orthogonal precoding operates at 2-3 dB lower SNR than unitary precoded integer forcing (UPIF), at an error rate of 10^{-5}. This is surprising because orthogonal precoding uses real values, whereas the physical channel as well as unitary precoding uses complex values. In addition, the proposed scheme has lower complexity. Orthogonal precoding outperforms UPIF type II in some scenarios and the X-precoder in high-order QAM schemes, e.g., 64- and 256-QAM [J4][C11].

(4) WP4: Multi-terminal Gaussian Networks

A new and promising technique for coded modulation in multi-terminal Gaussian networks and beyond is sparse regression codes, decoded using orthogonal approximate message passing (OAMP). OAMP is a low-cost iterative parameter-estimation technique that converges for a broad class of matrices, particularly right-unitarily-invariant matrices. We solved the problem of high complexity MMSE estimation used by OAMP by developing memory AMP (MAMP), which uses local memory instead of MMSE estimation [J2][C3]. Such systems naturally induce L-banded matrices, and interesting algebraic properties of such matrices were shown [J1].

For application to wireless communications, we showed that sparse regression codes using irregular clipping outperforms codes using regular clipping. Numerical results demonstrate that irregularly clipped SR codes achieve 2.2 dB gain in signal-to-noise-ratio (SNR) over regularly clipped SR codes, as shown in Fig. 5 [C6].

Publications

[J1] S. Huang, L. Liu, and B. M. Kurkoski, “Algebra of L-banded matrices,” IEEE Access, vol. 11, February 2023.

[J2] L. Liu, S. Huang, and B. M. Kurkoski, “Memory AMP,” IEEE Transactions on Information Theory, vol. 68, no. 12, pp. 8015-8039, 2022.

[J3] F. Zhou and B. M. Kurkoski, “Construction D' lattices for power-constrained communications,” IEEE Transactions on Communications, vol. 70, no. 4, 2022.

[J4] M. N. Hasan, B. M. Kurkoski, A. Sakzad, and E. Viterbo, “Steepest gradient-based orthogonal precoder for integer-forcing MIMO,” IEEE Transactions on Wireless Communications, no. 2, pp. 942-955, 2020

[C1] B. M. Kurkoski, “CRC-enabled lattices for multiuser communication.” Presentation at Information Theory and Applications Workshop, February 2023. Wyndham San Diego Bayside, California, USA, February 16.

[C2] J. Xue and B. M. Kurkoski, “Lower bound on the error rate of genie-aided lattice decoding,” in Proceedings of IEEE International Symposium on Information Theory, (Espoo, Finland), 2022.

[C3] L. Liu, S. Huang, and B. M. Kurkoski, “Sufficient statistic memory approximate message passing,” in Proceedings of IEEE International Symposium on Information Theory, 2022.

[C4] B.-Y. Tseng, B. M. Kurkoski, P. Mohr, and G. Bauch, “An FPGA implementation of two-input LUT based information bottleneck LDPC decoders,” in International Conference on Modern Circuits and Systems Technologies (MOCAST), 2022.

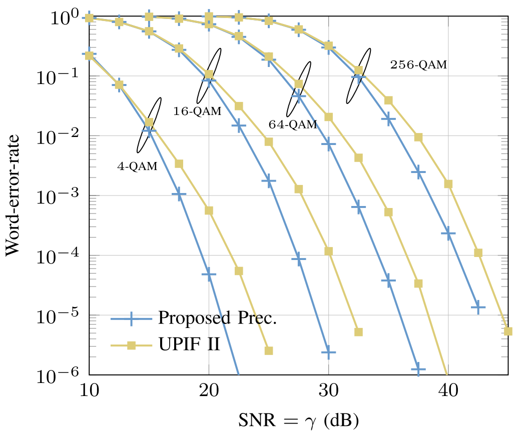

Figure 4: Orthogonal precoding operates at 2-3 dB lower SNR than unitary precoded integer forcing (UPIF), at an error rate of 10^{-5}, for 4x4 MIMO system.

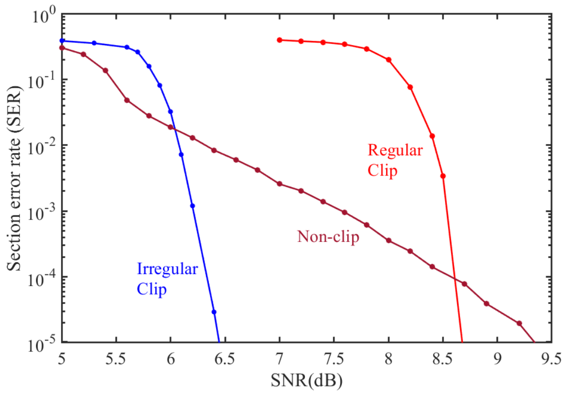

Figure 5: Our proposed irregular clipped SR codes perform 2.2 dB better than regular clipped, with no significant increase in complexity. Rate $R = 1$ code.

[C5] W. Wiriya and B. M. Kurkoski, "Reliability-based decoding of complex low-density lattice codes," in Proceedings of the IEEE Information Theory Workshop, (Kanazawa, Japan), October 2021.

[C6] W. Li, L. Liu, and B. M. Kurkoski, "Irregularly clipped sparse regression codes," in Proceedings of the IEEE Information Theory Workshop, (Kanazawa, Japan), October 2021.

[C7] L. Liu, S. Huang, and B. M. Kurkoski, "Memory approximate message passing," in Proceedings of IEEE International Symposium on Information Theory, (Melbourne, Australia), pp. 1379-1384, July 2021.

[C8] O. R. Ludwiniananda, N. Liu, K. Anwar, and B. M. Kurkoski, "Design of polar code lattices of small dimension," in Proceedings of IEEE International Symposium on Information Theory, (Melbourne, Austrlia), pp. 1011-1016, July 2021.

[C9] F. Zhou, A. Fitri, K. Anwar, and B. M. Kurkoski, "Encoding and decoding construction D' lattices for power-constrained communications," in Proceedings of IEEE International Symposium on Information Theory, (Melbourne, Australia), pp. 1005-1010, July 2021.

[C10] W. Wiriya and B. M. Kurkoski, "EM algorithm for DMC channel estimation in NAND flash memory," in Non-Volatile Memories Workshop, (San Diego, California, USA), March 2020.

[C11] M. N. Hasan, B. M. Kurkoski, A. Sakzad, and E. Viterbo, "Orthogonal precoder for integer-forcing MIMO," in Proceedings of IEEE International Symposium on Information Theory, (Paris, France), pp. 1187-1191, July 2019.

５．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　4件／うち国際共著　4件／うちオープンアクセス　2件）

１．著者名 Zhou Fan、Kurkoski Brian M.	４．巻 70
２．論文標題 Construction D’ Lattices for Power-Constrained Communications	５．発行年 2022年
３．雑誌名 IEEE Transactions on Communications	６．最初と最後の頁 2200～2212
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TCOMM.2022.3147235	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Obed Rhesa Ludwiniananda, Ning Liu, Khoirul Anwar, Brian M. Kurkoski	４．巻 2102.03998
２．論文標題 Design of Polar Code Lattices of Small Dimension	５．発行年 2021年
３．雑誌名 arXiv	６．最初と最後の頁 1-6
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Fan Zhou, Arini Fitri, Khoirul Anwar, Brian M. Kurkoski	４．巻 2102.04741
２．論文標題 Encoding and Decoding Construction D' Lattices for Power-Constrained Communications	５．発行年 2021年
３．雑誌名 arXiv	６．最初と最後の頁 1-6
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 無
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Ochiai Hideki, Mitran Patrick, H. Vincent Poor	４．巻 69
２．論文標題 Capacity-Approaching Polar Codes With Long Codewords and Successive Cancellation Decoding Based on Improved Gaussian Approximation	５．発行年 2021年
３．雑誌名 IEEE Transactions on Communications	６．最初と最後の頁 31～43
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TCOMM.2020.3030057	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Hasan Mohammad Nur、Kurkoski Brian M.、Sakzad Amin、Viterbo Emanuele	４．巻 19
２．論文標題 Steepest Gradient-Based Orthogonal Precoder for Integer-Forcing MIMO	５．発行年 2020年
３．雑誌名 IEEE Transactions on Wireless Communications	６．最初と最後の頁 942～955
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TWC.2019.2950010	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Matsumine Toshiki、Ochiai Hideki	４．巻 23
２．論文標題 A Novel PAPR Reduction Scheme for Polar-Coded OFDM Systems	５．発行年 2019年
３．雑誌名 IEEE Communications Letters	６．最初と最後の頁 2372～2375
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LCOMM.2019.2943334	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計9件（うち招待講演　2件／うち国際学会　7件）

１．発表者名 Wiriya Warangrat、Kurkoski Brian M.
２．発表標題 Reliability-Based Decoding of Complex Low-Density Lattice Codes
３．学会等名 Proceedings of the IEEE Information Theory Workshop（国際学会）
４．発表年 2021年

１．発表者名 Li Wencong、Liu Lei、Kurkoski Brian M.
２．発表標題 Irregularly Clipped Sparse Regression Codes
３．学会等名 Proceedings of the IEEE Information Theory Workshop（国際学会）
４．発表年 2021年

１．発表者名 Zhou Fan、Fitri Arini、Anwar Khoirul、Kurkoski Brian M.
２．発表標題 Encoding and Decoding Construction D' Lattices for Power-Constrained Communications
３．学会等名 Proceedings of IEEE International Symposium on Information Theory（国際学会）
４．発表年 2021年

１．発表者名 Ludwiniananda Obed Rhesa、Liu Ning、Anwar Khoirul、Kurkoski Brian M.
２．発表標題 Design of Polar Code Lattices of Finite Dimension
３．学会等名 Proceedings of IEEE International Symposium on Information Theory（国際学会）
４．発表年 2021年

１．発表者名 Liu Lei、Huang Shunqi、Kurkoski Brian M.
２．発表標題 Memory Approximate Message Passing
３．学会等名 Proceedings of IEEE International Symposium on Information Theory（国際学会）
４．発表年 2021年

１．発表者名 Hasan Mohammad Nur、Kurkoski Brian M.、Sakzad Amin、Viterbo Emanuele
２．発表標題 Orthogonal Precoder for Integer-Forcing MIMO
３．学会等名 2019 IEEE International Symposium on Information Theory（国際学会）
４．発表年 2019年

１．発表者名 Brian M. Kurkoski
２．発表標題 From classification to quantization: Machine learning for communications
３．学会等名 Symposium on Future of Telecommunication Technologies (Kuala Lumpur, Malaysia)（招待講演）
４．発表年 2019年

１．発表者名 Brian M. Kurkoski
２．発表標題 Introduction to lattice coding theory
３．学会等名 Studium Generale at Telkom University (Bandung, Indonesia)（招待講演）
４．発表年 2019年

１．発表者名 Y. Yajima and H. Ochiai
２．発表標題 On Design of Multilevel Coded Modulation Based on CRC-Concatenated Polar Codes
３．学会等名 2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC)（国際学会）
４．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関