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研究課題名（和文）高密度フラッシュメモリシステムに適した信号処理・符号化方式の開発

研究課題名（英文）Signal Processing and Coding Methods for High-Density Flash Memory Systems

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研究成果の概要（和文）：フラッシュメモリの大容量化・長寿命化の実現のために新しい信号処理・符号化方式の開発とその性能評価を行った。フローティング符号(WOM符号)の最適符号構造に関して格子理論に基づき検討を重ねた結果、ある連続集合と格子の共通部分から成る最適符号構造を開発した。信頼度の向上を目指して開発した、８次元のE8格子とReed-Solomon符号を組み合わせた符号化変調方式は、従来のBCH符号を利用するフラッシュメモリ符号化方式と比べてSN比において1.8dBの利得を与えるなど優れた性能を持つことが示されている。さらに、相互情報量を最大化する方法に基づき、効率的な通信路量子化手法を開発した。

研究成果の概要（英文）：We developed and characterized new signal processing and coding methods to improve the capacity and longevity of flash memories. We investigated optimal WOM code constructions based on lattice theory and developed an optimal code construction using the intersection of a lattice and some shaping region. To increase reliability, our coded modulation method combining lattices and Reed-Solomon codes improves the SNR by 1.8 dB over existing flash memory codes using BCH codes. And, we developed an effective channel quantization method based on the maximization of mutual information.

研究分野：情報科学

科研費の分科・細目：電気電子工学・通信・ネットワーク工学

キーワード：フラッシュメモリ　誤り訂正符号　フローリング符号　WOM符号　信号処理　国際研究者交流

１．研究開始当初の背景

Flash memories are semiconductor data storage devices that have fast access speeds, low power consumption and mechanical reliability. Because of this, flash memories have been used in digital cameras and portable audio players, but now in smartphones, personal computers and even in data centers.　Flash memory capacities are always increasing, but as the density increases, reliability and longevity of flash memories decrease. To solve these problems suitable coding methods are necessary, and an information theoretic approach is desired.

２．研究の目的

This project has three major goals. (i) development of new coding and information theoretic methods to correct errors and increase the longevity of flash memories. (ii) Strong, hardware-suitable error-correction algorithms, to reduce power consumption and increase decoding speed in flash memories. (iii) Promoting international collaboration and interaction with researchers overseas.

３．研究の方法

The research methods consist of design of error-correcting codes, algorithm construction and their software implementation. By separating into the three parts, we can deal with the problems systematically.

４．研究成果

Several new coding methods, algorithms and implementations to increase the reliability of flash memory systems were obtained; major, representative results are described here.

(1) For error-correction in flash memories, multi-level flash memories can be viewed as a coded-modulated system. A new construction was proposed which combined lattices and Reed-Solomon error-correcting codes. This construction is suitable for the hardware architecture of flash memory systems, if the low-complexity lattice decoder is placed on the flash chip, to access soft-information.

This system using an E8 lattice and high-rate Reed-Solomon codes could achieve 1.8 dB gain over the conventional system, which is BCH codes using Gray-level labeling.　This 1.8 dB gain allows high-density flash memories to tolerate more noise and be more reliable, and is shown in Figure 1.

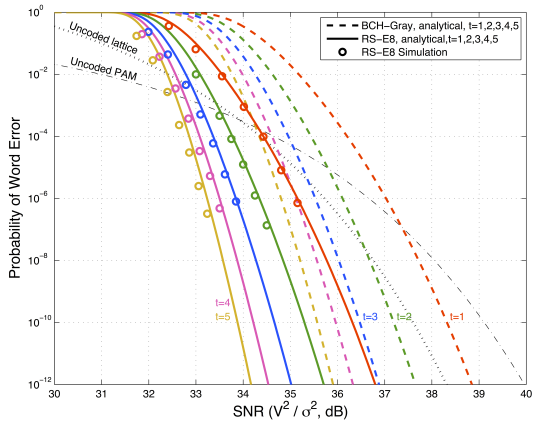

Figure 1. Word-error rate performance vs. SNR.　The proposed scheme shows 1.8 dB gain over conventional BCH-coded modulation.

(2) WOM codes are “write once memory” codes and allow re-writing a flash memory without erasing it.　Since erasing flash memory shortens its longevity, WOM codes can increase the longevity of flash memories.　At the same time, because of the noise in flash memories, error-correction capability is needed.

Since lattices have error correction capability, we showed that lattice-based WOM codes can be designed. The key is to consider a “hyperbolic shaping region”. For dimension n=2, a hyperbolic shaping region is shown in Figure 2. The hyperbola is the optimal shape, in the sense of making the number of writes independent of the data.　Moreover, we showed that this construction achieves the capacity of Fu-Han Vinck WOM code capacity.　The error-correction capability and the WOM capability are “separable,” that is, related to each other only by the code-rate tradeoff. The significance of this result is application of geometry to information theoretic WOM code capacities.

(3) A new construction for index-less indexed flash codes (ILIFC) was described. It has higher average number of rewrites than existing codes.　The average number of rewrites can be described by a Markov chain model.

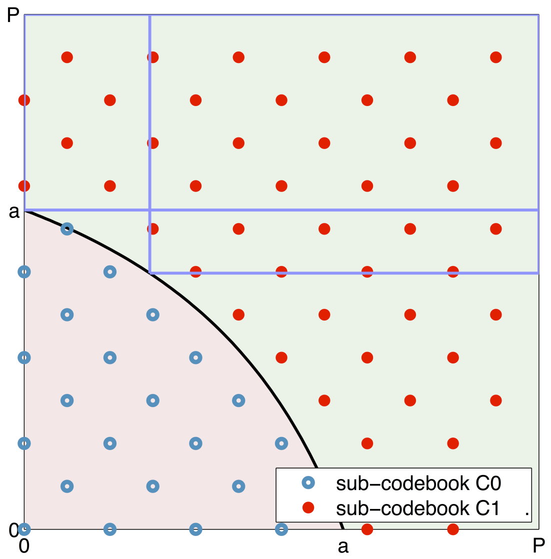

Figure 2. Hyperbolic shaping region for two-write WOM code. The blue lattice points in the pink region form the codebook for the first write. The red lattice points in the green region form the codebook for the second write.

(4) Because flash memories have noise, WOM codes which can tolerate noise are needed. New binary WOM codes which both allow re-writing and also correct errors was given. The new construction has higher coding rate than the existing method, for a fixed number of errors corrected.

(5) We developed new quantization methods. As a fundamental information-theoretic result, it has applications both to quantization of the signal read from the flash cell, and the implementation of high-speed low-energy LDPC decoders. In the basic scenario, we quantize the output of a discrete memoryless channel with M outputs to K quantizer outputs with K < M. When the channel input is binary, we gave an algorithm which maximizes the mutual information between the channel input and quantizer output.

In addition, this grant also supported international collaborations and "Workshop on Coding for Flash Memories," which gathered international and domestic researchers. The workshop was held two times:

- May 23-24, 2013 at Matsuya-Sensen in Fukui-ken, Awari-shi (5 presentations)
- March 15, 2012 at the University of Electro-Communications in Tokyo-to, Chofu-shi (7 presentations, including 3 invited)

Refer to the URL:
http://flashworkshop.org/

Also, we invited Eitan Yaakobi, of Caltech and the University of California San Diego (now associate professor at Technion, Israel) to give a lecture "Recent Advances on Coding for Flash Memories." His visit led to 2 international conference presentation and 1 journal paper.

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〔その他〕
ホームページ:
① http://www.flashworkshop.org/
② http://brian.kurkoski.org/

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