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Turbo Product Codes Decoding Algorithm with Weighted HIHO for Energy-efficient Wireless Sensor Network

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Abstract

Complexity and energy-efficiency are viewed as two main factors of design error correct coding for the wireless sensor networks. First of all, this paper presents a Weighted Hard-Input Hard-Output (WHIHO) iterative decoding algorithm with the low complexity when the required bit error rate (BER) is satisfied for wireless sensor nodes. A reliability matrix from four different aspects of the decoding process, properly weighs and combines their respective reliability measures, and then employs the combined measure to make a judgment with regard to whether each received bit is correct or not. Next, the energy efficiencies of turbo product codes using HIHO and WHIHO decoding algorithm are analyzed. Simulation results in a BER curve indicating that the WHIHO decoding algorithm can achieve a better tradeoff between reliability and complexity, which compared with conventional HIHO and soft-input and soft-output (SISO) decoding algorithms. The simplicity and effectiveness of WHIHO decoding algorithm makes it a promising candidate for the application for wireless sensor network.

Keywords: *Wireless sensor networks; Energy-efficient; product codes; Weighted HIHO decoding*

1. Introduction

The Wireless Sensor Network (WSN) is a multiple hops self-organizing Network system, by wireless communication mode to form, assigned in monitoring area by a large number of Sensor nodes. Its purpose is collaboration to perceive, collection and processing Network coverage area by monitoring object information, and sent to the observer. The WSN is being widely applied in various control oriented scenarios and becoming increasingly important. For these applications, wireless communication must guarantee some requirements such as high reliability, low latency, security, energy-efficient and so on when the resource-constrained sensor nodes are employed. Therefore, reliability transmission over wireless medium among simpler devices becomes more challenging in some unfriendly environment. Error Control Coding (ECC) is an important approach to improve link reliability. At the same time, it introduces extra encoding and decoding complexity and transmission overheads. Hence for the energy limited and simpler sensor nodes, energy-efficient and low complexity error control codes should be used. However, some advanced error control codes are also encouraged to be adopted in order to achieve more coding gains in many scenarios like mobile tracking.

Turbo code has been presented in order to obtain powerful error correction ability with reasonable decoding complexity [1]. This code offers the performance that is close to

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Shannon's theoretical limit over additive white Gaussian noise (AWGN) channels. Turbo code can be classified into Convolutional Turbo Code (CTC) and Block Turbo Code (BTC) according to the component code used. The BTC is also called as turbo product code (TPC). TPC codes are desirable for many reasons, among which it's superior BER performance and simple interleaver structure is most notable [2]. Depending on what underlying component codes are used, the TPC code can exhibit very different code length, code rate, code performance, as well as complexity. A simple but slightly weaker choice is Single-Parity Check (SPC) codes (*i.e.*, SPC-TPC codes), but a more decent and more popular choice that promises considerably better performance is BCH codes (*i.e.*, BCH-TPC codes). Another notable feature of TPC is its high parallelizability, which allows for fast hardware implementation. Additionally, TPC codes are easy to describe, as many parameters of the overall code are the products of the respective parameters of its component codes.

The decoding of a TPC generally involves an iterative process, in which row decoders and column decoders take turns to refine the decisions. To harness the full potential of the iterative decoding architecture requires the row decoders and columns decoders to be Soft-Input and Soft-Output (SISO), either performing Maximum A Posteriori (MAP) probability decoding or near-MAP decoding. However, SISO decoders are very difficult to design and very expensive to implement, and for many practical component codes (such as BCH codes), the SISO decoding technology is either heuristic or incurring a long delay. Generally, decoding algorithm used in each component codeword of a TPC is a SISO decoding scheme. The soft decoding requires many hard decision decoding (HDD) operations and a considerable number of arithmetic operations. Therefore, it is a great challenge for a resource-constrained sensor node in sensor network.

An alternative approach to soft-iterative decoding is hard-iterative decoding, which uses Hard-Input and Hard-Output (HIHO) component decoders [3-5]. It is apparent that HIHO decoder has much lower complexity and requires one HDD operation for each component decoding processing and do not require any arithmetic operations, hence it is much simpler than the SISO decoder. However, the HIHO schemes are inferior to the SISO ones in terms of reliability so that it cannot meet the requirements of higher error floor like fiber optical communication, largely due to error propagation/amplification and closed-chains error patterns. To handle the closed-chains error patterns, Ref [5] proposes to estimate the closed-chains error pattern for the first time to locate the possible error positions and next use an appropriate erasure decoding algorithm to correct them. Such a method can attain more gain at the cost of a higher complexity. In order to achieve reliability improvement for the HIHO decoders, Ref [6] and [7] introduced two schemes. The scheme using non-sequential decoding algorithm [6] leads to less additional complexity. In Ref [7], an approach is given and achieves better bit error rate (BER) performance due to overcoming the effect of closed-chains error pattern. In general, the question of effective decoding boils down to the problem of finding an algorithm or strategy that strikes the best trade-off between complexity and performance, depending on the application requirements. This series of study, though makes sense both theoretically and practically, does pose a lot of changes, and therefore motivates our research work and the details are given below.

The contribution of this paper is the proposition of a new HIHO decoding algorithm for TPC codes in general and BCH-TPC codes in particular, which enables the code to deliver a very promising performance with reasonable complexity. We know that HIHO decoders inevitably involve bit-flips. It appears that the existing algorithms have performed bit-flips too readily and hastily in each generation. Our extensive study reveals that the undesirable performance of HIHO iterative decoding is to a quite large extent attributed to "overdo in bit-flips", which causes not only the erroneous bits, but also a good number of correct bits, to be flipped. This in turn leads to undesirable error propagation, and causes the overall decoder to swing around, rather than converges steadily towards the correct codeword. To solve this problem, we propose to perform bit flipping in a more judicious manner. Specifically, we propose to carefully evaluate four different aspects of the decoding process, row decoding only, row- followed-by-column decoding, column decoding only, and column-followed-by-row decoding, to properly weigh and combine their reliability measures and to use the combined measure to make a judgment of whether any particular bit should be flipped or not. Such a judicious judgment for bit-flips, although simple and fast, turns out to be very effective. This code yields a good performance when the WHIHO decoding algorithm is used. Considering the very low decoding complexity and the very low error floor, we advocate our algorithm (together with the BCH-TPC code) as a promising algorithm for application in wireless sensor networks.

The rest of the paper is organized as follows. Section 2 provides a brief view about TPC and the WHIHO decoding algorithm. Energy evaluation of TPC with BCH component codes is given in Section 3. Simulation and discuss are shown in Section 4. And finally conclusions are provided in Sections 5.

2. Turbo Product Codes and WHIHO Decoding Algorithm

A turbo product code is constructed from an array of identical row codes and an array of identical column codes, arranged in a two-dimensional row-by-column array. Both row codes and column codes are systematic linear block codes. The encoder for the TPC consists of the serial concatenation of the row encoder and the column encoder, both of which are considered as component encoders [8]. Let $\mathbf{C}^{i}\,(i=1,2)$ be the respective row code and column, which has the parameters $(n_i, k_i, d_{\min}^{(i)})$ where n_i, k_i and $d_{\min}^{(i)}$ stand for codeword length, the overall number of information bits and minimum Hamming distance, respectively. The product code $\boldsymbol{C}$ has parameters $(n^*, k^*, d_{\min}^*)$, $n^* = n_1 \times n_2$, $k^* = k_1 \times k_2$, $d_{\min}^* = d_{\min}^{(1)} \times d_{\min}^{(2)}$. In a conventional HIHO TPC decoder, all the rows are decoded in a batch, followed by decoding of all the columns, and so on. Such a hard iterative decoding process is conceptually simple and follows behind with the renowned soft-iterative decoding paradigm. However, when a component decoder makes an incorrect decision, a good number of correct bits are also flipped along with the erroneous ones. In order to overcome the drawback, we utilize a combined reliability matrix from four different component decoding processes to make decisions on the received bits.

In this section, an iterative decoding algorithm for HIHO TPC is devised based on reliability matrix W constructed by the results of four different component decoding processes. The four component decoding processes are separately row-decoding which is to decode row by row independently, column-decoding which is to decode column by column independently, row-column decoding which is to decode column by column after decoding row by row, and column-row decoding which is to decode row by row after decoding column by column.

Reliability measurement for component codes is based on the estimated number of errors in received sequence. The reliability matrix's elements represent the bits' reliability of being flipped. Then, based on the four estimated results, decoder computes the final reliability of each bit in the received TPC matrix and makes a decision for each bit based on the threshold. And the decision results are the output of current iteration process. The next iteration will be operated based on the previous output until the stop condition is satisfied. And the final reliability matrix is expressed by $\boldsymbol{W} = \left[w_{i,j} \right]_{n_C \times n_R}$, where $w_{i,j}$ represents the reliability of the bit that locate in i-th row and j-th column in one iteration, which can be computed according to

$$w_{i,j} = w_{i,j}^{R} + w_{i,j}^{C} + w_{i,j}^{RC} + w_{i,j}^{CR} \tag{1}$$

Where the reliability value $w_{i,j}^{R}$, $w_{i,j}^{C}$, $w_{i,j}^{CR}$ and $w_{i,j}^{RC}$ represent separately the reliability matrix constructed by row decoding, column decoding, row-column decoding and column-row decoding. They can be obtained by the estimated errors number $\hat{e}$ in component code. The proposed algorithm is summarized as follows.

Initiate reliability matrix and iterations counter, $\boldsymbol{W} = \left[w_{i,j} \right]_{n_C \times n_R} = [0]_{n_C \times n_R}$, $L = 1$.

Set the reliability threshold $\delta(\delta = 0)$ and the maximum number of iterations $I_{\max}$.

a. Compute $w_{i,j}^{R}$, $w_{i,j}^{C}$, $w_{i,j}^{CR}$ and $w_{i,j}^{RC}$ by row decoding, column decoding, row-column decoding and column-row decoding. The reliability values $w_{i,j}^{R}$, $w_{i,j}^{C}$, $w_{i,j}^{CR}$ and $w_{i,j}^{RC}$ depend on the probability of different errors number estimation in received sequence.

b. Update reliability matrix $\boldsymbol{W}$ based on step 1 and equation (1).

c. Flip the bits based on reliability matrix $\boldsymbol{W}$, for $i, j = 1, 2, \cdots, n_C(n_R)$. If $w_{i,j} > \delta$, then $\hat{c}_{i,j}^{L} = \hat{c}_{i,j}^{L-1} \oplus 1$, else $\hat{c}_{i,j}^{L} = \hat{c}_{i,j}^{L-1}$.

d. $L = L + 1$.

e. If $L > \mathrm{I}_{\max}$ or all $w_{i,j} < \delta$, then $\left[\hat{c}_{i,j} \right]_{n_C \times n_R} = \left[\hat{c}_{i,j}^{L} \right]_{n_C \times n_R}$, otherwise, reset $\left[w_{i,j} \right]_{n_C \times n_R} = [0]_{n_C \times n_R}$, and return to step 1.

3. Energy-efficiency Analysis

WSN plays a more and more important role in various applications which oriented control. In these scenarios, for wireless communication between distributed power limited sensor nodes, some of the features must be guaranteed, such as: high reliability, low delay and predictable data transmission, *etc.*, harsh environment, it is a challenging task to ensure these features. ECC is a classical method to enhance the reliability of data link, and it can reduce the required transmission power. But, at the same time, it will introduce extra complexity of coding and decoding and consumption of transmission. The error control coding must be energy-efficient coding and with low complexity, which is determined by limited sensor node energy and simple structure. However, in order to achieve higher coding gain, some advanced error control coding also be encouraged to use sometimes.

All kinds of the super ability of error correction code word was put forward such as LDPC code and Turbo code, for now, it is no longer a difficult problem to let error control coding meet the error correction capability of wireless sensor network. Now, another problem which wireless sensor network face is the energy-efficiency of error control coding. In order to prolong the life of sensor nodes, the communication protocol between the nodes and error control coding must be efficient, because the sensor nodes are energy limited. So, what kind of error control coding is efficient [9] gives the definition of energy-efficiency, which a lot of literature make it as a standard of wireless sensor network of error control technology [10-11]. The following we will the analyze the energy-efficiency with standard HIHO algorithm and weighted iterative hard decision decoding algorithm, which refer to [9] definition of energy efficiency.

Sensor nodes have small battery capacity and cannot be charged timely in most application scenarios. Hence, though the application of wireless sensor seems to be attractive, the limited onboard energy is a major challenge when we want to practically take advantage of WSN on a large scale. The design of energy-efficient strategies with required BER is quite important. Existing optimal error control techniques with the aim to maximize the throughput which cannot be directly applicable to energy constrained WSN. For energy- efficient communication, the sum of the circuit energy consumption and transmission energy consumption in sensor nodes is considered and chosen as the optimization metric. This section discusses the energy efficiencies of TPC with HIHO and WHIHO decoding algorithm, and continues to use the assumption and definition in Ref. [9] with the definition according to

$$\eta = \eta_e (1 - PER) \tag{2}$$

Where PER is the short form of packet error rate and $1-PER$ stands for data reliability, and η_e denotes the energy throughput and the proportion of energy consumption. Energy efficiency η represents the useful fraction of the total energy consumption in a communication link [9].

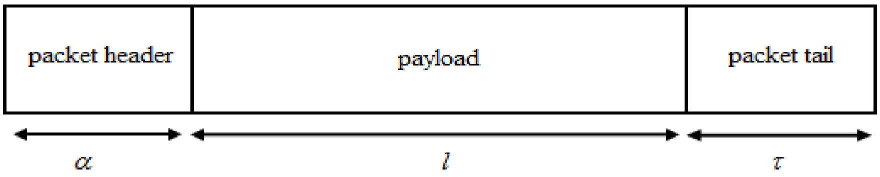

Figure 1. Format Chart of Data Packet in Wireless Sensor Network

We define a data packet format including α bits header, l bits payload and τ bits tail, as shown in Figure 1.

Due to the encoding energy is very small compared with decoding energy, the encoding energy is assumed to be negligible.

E_b is expressed as the energy E_b needed to communicate one information bit ,which is concrete expressed as：

$$E_b = E_t + E_r + \frac{E_{dec}}{l} \tag{3}$$

where E_{dec} stands for the decoding energy per codeword. E_t and E_r are represent the energy consumption in transmitter and receiver respectively, and the concrete expression as follows:

$$E_t = \frac{(P_{te} + P_O)\dfrac{(l+\alpha+\tau)}{R} + P_{tst} T_{tst}}{l} \tag{4}$$

$$E_r = \frac{P_{re}\dfrac{(l+\alpha+\tau)}{R} + P_{rst} T_{rst}}{l} \tag{5}$$

Where $P_{te/re}$ stands for the power consumption of transmitter/receiver electronics, $P_{tst/rst}$ stands for the start-up power consumption of transmitter/receiver, $T_{tst/rst}$ stands for start-up time of transmitter/receiver , P_O stands for output power of transmitter ,and R stands for data rate.

We simplified formula (3) with the wireless parameters Ω_1 and Ω_2 , the concrete expression as follows.

$$E_b = \Omega_1 + \Omega_1 \frac{\alpha + \tau}{l} + \frac{\Omega_2 + E_{dec}}{l} \tag{6}$$

Where Ω_1 stands for useful energy of communicate one information bit. Ω_2 stands for the start-up power consumption of transmitter/receiver electronics. For the given radio transceiver and data rate, parameters Ω_1 and Ω_2 are constant. For example, they were 1.85 $\mu J / bit$ and 24.86 μJ according to Ref [12].So the E which stand for total energy efficiency can be expressed as

$$\eta_e = \frac{\Omega_1 l}{\Omega_1 (l + \alpha + \tau) + \Omega_2 + E_{dec}} \tag{7}$$

Then we rewrite the energy efficiency formula as follows:

A) Without error control coding,

$$\eta = \frac{\Omega_1 l}{\Omega_1 (l + \alpha) + \Omega_2} (1 - P_b)^{k+\alpha} \tag{8}$$

B) For TPC codes with BCH as component codes [12],

$$\eta = \frac{\Omega_1 (n^* - h - \tau)}{\Omega_1 k^* + \Omega_2 + E_{dec}} (1 - PER) \tag{9}$$

Where P_b is raw channel BER, and $n^* = l + h + \tau$, $k^* = l + h$. Based on binary BCH decoding using Berlekamp-Massey (BM) and Chien's search (CS) algorithm, E_{dec} for a TPC with t error correcting capability binary BCH code of length n during one iteration can be given as

$$E_{dec} = n(2nt + 2t^2 + 2nt + 2t^2)(E_{add} + E_{mult}) \tag{10}$$

Where E_{add} And E_{mult} stand for the energy consumption of an addition or multiplication operation in finite fields $\mathrm{GF}(2^m)$.When we ignore the weight calculation which have relatively small energy consumption, we propose the energy consumption formula for weighted hard-input and hard-output iterative decoding can be expressed as $E_{dec}^W = 2E_{dec}$. Where E_{add} and E_{mult} are the energy consumption of the addition and multiplication of field elements in $\mathrm{GF}(2^m)$. Consumed energy of the proposed weighted decoding algorithm can be expressed as $E_{dec}^W = 2E_{dec}$ when assuming the energy of calculating weighted value is negligible.

4. Simulation and Discussion

Monte Carlo simulations were conducted to evaluate the performance of the WHIHO algorithm. The encoded bits are modulated by BPSK and transmitted through AWGN channel.

Simulation results are presented using BCH (31, 21, 5) codes as component codes in Figure 2. The BER for standard HIHO TPC and non-sequential decoding algorithm are also presented with 1, 2, 5 and 30 iterations Compared to the standard HIHO decoder, we can get 0.5 dB coding gain at the BER of 10^{-4} for 30 iterations and 0.45 dB coding gain for 5 iterations with lower complexity. And the proposed weighted decoding also provides an extra 0.2 dB of coding gain at the BER of 10^{-4} compared to the non-sequential decoding using 30 iterations and 0.15 dB coding gain for 5 iterations. The complexity of the proposed hard decision iterative decoding algorithm is lower than that of SISO decoding algorithm with Chase-II and can achieve better tradeoff between coding gain and complexity for TPC in sensor network with resource-constraint nodes.

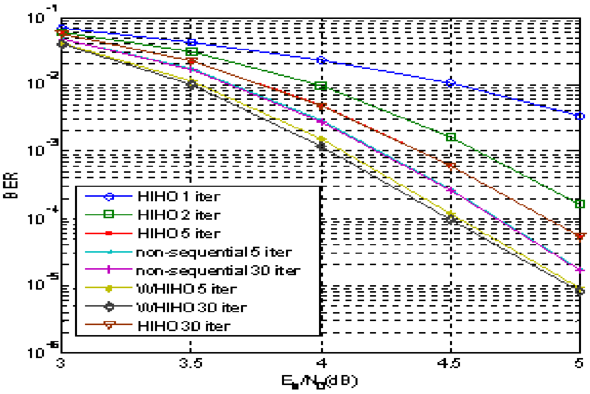

Figure 2. BER of Different Algorithms

Next, we examine the energy efficiencies of TPC using HIHO and WHIHO decoding algorithm through simulation. The energy efficiency are listed in Table 1 with different raw channel BER $P_b = 6 \times 10^{-3}$ and $P_b = 3 \times 10^{-3}$ using different BCH component codes with the same error correcting capacity *t*=1, adopting non-coherent binary frequency shift key (NC-BFSK) over Rayleigh channel. We can obtain the following observations from Table 1. TPC with WHIHO can improve the energy efficiency of communication among wireless sensors network. For $P_b = 6 \times 10^{-3}$ in Table 1, energy efficiency of TPC with BCH (63, 57) component codes is greater than that of other codes. For $P_b = 3 \times 10^{-3}$ in Table 1, (127, 120) codes can improve the energy efficiency. Therefore, energy efficient error control codes are different for different raw channel BER. When we design the TPC, the radio and channel parameters need to be estimated, and the optimal code parameters are then determined for a given set of radio and channel parameters to maximize the energy efficiency metric. And Table 1 also shows that the proposed WHIHO algorithm has further improvement over HIHO on energy efficiency.

Table1. The Energy Efficiency for TPC using different algorithm

Component codes	Code rate	$P_b = 6 \times 10^{-3}$		$P_b = 3 \times 10^{-3}$	
		HIHO	WHIHO	HIHO	WHIHO
(31,26)	0.8387	0.6764	0.6765	0.6773	0.6773
(63,57)	0.9048	0.7827	0.7965	0.8100	0.8105
(127,120)	0.9449	0.1980	0.2310	0.8468	0.8665

5. Conclusions

We proposed an energy efficient TPC using WHIHO decoding algorithm for WSN. Firstly, a WHIHO iterative decoding algorithm is presented to achieve tradeoff between reliability and complexity of TPC based on the reliability derived from four different decoding processes. Secondly, we investigate the energy efficiency of TPC in WSN. Finally, Simulation verified that our method is energy efficient and can achieve a better tradeoff between coding gain and complexity for WSN with simple nodes.

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References

[1] C. Berrou, A. Glavieux and P. Thitimajshima, “Near Shannon limit error correcting coding and decoding: turbo-codes”, IEEE International Conference on Communication, Geneva, Switzerland, **(1993)**.

[2] R. M. Pyndiah, “Near-optimum decoding of product codes: block turbo codes”, IEEE Transaction on Communication, vol. 46, no. 8, **(1998)**.

[3] A. A. Dweik and B. Sharif, “Non-Sequential Decoding Algorithm for Hard Iterative Turbo Product Codes”. IEEE Transactions on Communications, vol. 57, no. 6, **(2009)**.

[4] A. A. A. Shaikhi and M. A. Kousa, “Modified Algorithm for Hard Decision Decoding of Product Codes”, Proceedings of the Wireless Communications and Networking Conference, vol. 3, **(2004)**, pp. 1760-1763.

[5] A. A. Dweik and B. Sharif, “Closed-Chains Error Correction Technique for Turbo Product Codes”, IEEE Trans. on Communications, vol. 59, no. 3, **(2011)**.

[6] A. J. A. Dweik and B. S. Sharif, “Non-sequential decoding algorithm for hard iterative turbo product codes”, IEEE Transactions on Communication, vol. 57, no. 6, **(2009)**.

[7] A. J. A. Dweik and B. S. Sharif, “Closed-chains error correction technique for turbo product codes”, IEEE Transactions on Communication, vol. 59, no. 3, **(2011)**.

[8] Z. P. Shi, L. Zhou, X. Fan and Y. Yang, “HIHO Decoding Algorithms of Turbo Product Codes for High Rate Optical Communications”, China Communication, vol. 9, no. 6, **(2012)**.

[9] Y. Sankarasubramaniam, I. F. Akyildiz and S. W. Mclaughlin, “Energy efficiency based packet size optimization in wireless sensor networks”, IEEE international Workshop on Sensor Network Protocols and Applications, Anchorage, AK, United States, **(2003)**.

[10] Z. H. Kashani and M. Shiva, “BCH coding and multi-hop communication in wireless sensor networks”, International Conference on Embedded and Ubiquitous Computing, Bangalore, India, **(2008)**.

[11] H. Karvonen, Z. Shelby and C. P. Raez, “Coding for energy efficient wireless embedded networks”, International Workshop on Wireless Ad-hoc Networks, Oulu, Finland, **(2004)**.

[12] “ASH Transceiver Designer's Guide”, RFM-TRIMM Transceive, **(2004)**.

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