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A NON-BINARY TURBO TRELLIS CODE MODULATION-BASED 3-D MAP ALGORITHM

RAAD H. THAHER

College of Engineering, Al-Mustansiriyah University, Baghdad, Iraq

ABSTRACT

This paper presents anon-binary Turbo Trellis Coded Modulation (TTCM) decoder-based multidimensional 3-D (Maximum A Posteriori) MAP algorithm.

The proposed system deals with Non-binary error control coding of the TTCM scheme for transmissions over the AWGN channel. The idea of Non-binary codes has been extended for symbols defined over rings of integers, which outperform binary codes with only a small increase in decoding complexity.

The basic mathematical concepts are necessary for working with Non-binary error-correcting codes are Groups, Rings and Fields. The simulation results show that the performance of the non-binary TTCM decoding algorithm outperforms the binary decoding methods.

KEYWORDS: Turbo Codes, TTCM, Non-Binary Error Correcting Codes, Groups, Rings of Integers, MAP Algorithm

INTRODUCTION

Digital signals are more reliable in a noisy communications environment. They can usually be detected perfectly, as long as the noise levels are below a certain threshold. Digital data can easily be encoded in such a way as to introduce dependency among a large number of symbols, thus enabling a receiver to make a more accurate detection of the symbols. This is called error control coding.

Advances in coding, such as turbo [1] and low density parity check codes [2], made it feasible to approach the Shannon capacity limit [3] in systems with a single antenna link. Significant further advances in spectral efficiency are available through increasing the number of antennas at both the transmitter and the receiver [4, 5, 6].

Further performance gains can be achieved by using non-binary codes in the coded modulation scheme, but with an increase in the decoding complexity [7]. Non-binary codes are the most commonly used error-correcting codes and can be found in optical and magnetic storage, high-speed modems and wireless communications. When conventional coding techniques are introduced in a transmission system, the bandwidth of the coded signal after modulation is wider than that of the uncoded signal for the same information rate and the same modulation scheme. In fact, the encoding process requires a bandwidth expansion that is inversely proportional to the code rate, being traded for a coding gain.

The basic principle of CM [8] is that it attaches a parity bit to each uncoded information symbol formed by m information bits according to the specific modulation scheme used, hence doubling the number of constellation points to 2^{m+1} compared with that of 2^m in the original modem constellation. This is achieved by extending the modulation constellation, rather than expanding the required bandwidth, while maintaining the same effective throughput of m bits per symbol, as in the case of no channel coding. As trellis-coded modulation is an extension of binary coding methods to larger signal constellations, so is turbo-coded modulation the extension of turbo coding principles to include larger signal constellations. There are very few changes necessary to accommodate higher signaling alphabets, and therefore higher spectral efficiencies.

Among the various CM schemes, TCM [9] was originally designed for transmission over Additive White Gaussian Noise (AWGN) channels. TTCM [10] is a more recent joint coding and modulation scheme which has a structure similar to that of the family of binary turbo codes, but employs TCM schemes as component codes. Both TCM and TTCM employ set-partitioning-based constellation mapping [11], while using symbol-based turbo inter leavers and channel inter leavers. Another CM scheme, referred to as BICM [12], invokes bit-based channel inter leavers in conjunction with grey constellation mapping. Furthermore, iteratively decoded BICM [13] using set partitioning was also proposed.

Q. Mao et al., 2012 [14] proposed a novel Turbo- based encryption scheme using dynamic puncture mechanism, the error correction capability of the proposed coding scheme is as good as the normal Turbo code at the same coding rate. By periodically eliminating some bits from the output of the recursive systematic convolutional encoders of the Turbo code, a higher coding rate can be achieved. R. A. Carrasco et al., 2009 [15] presents the theory of non-binary error control coding in wireless communications and expected that the non-binary turbo decoding is an area of coding theory that has not received much attention. However, with non-binary LDPC codes recently becoming more popular, it would expect non-binary turbo codes to perform just as well and this would be an interesting area of research for the future.

NON-BINARY CODED MODULATION

In 1994, Baldini and Farrell [16] introduced a class of non-binary Block Coded Modulation (BCM) code over rings of integers suitable for M-PSK and M-QAM.

The idea of non-binary BCM codes is to transmit m bits per channel symbol by using a modulator with $q > 2^m$ waveforms to accommodate the extra redundancy. The non-binary BCM encoder structure is shown in Figure 1. The binary source generates $m + 1$ parallel bits, which are Gray mapped onto one of 2^{m+1} channel symbols $a_i \in \mathbb{Z}_q$, i= 0, 1,..., $k-1$. These are then fed to the multi-level encoder to generate the BCM coded symbols $x_i \in \mathbb{Z}_q$,i = 0, 1 ... n, which will increase the minimum Euclidean distance.

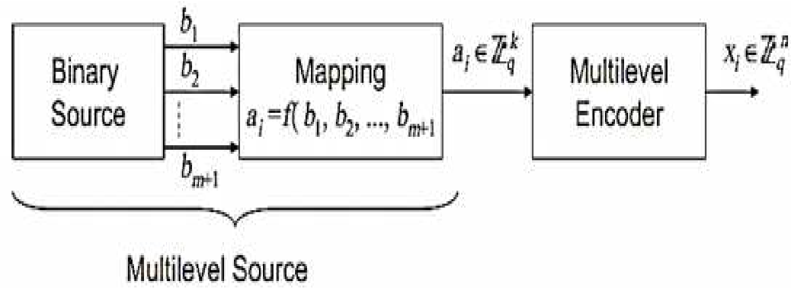

Figure 1: Non-Binary BCM Encoder Structure

MAXIMUM-A-POSTERIORI DECODING

The usual maximum likelihood (ML) detection is a hard-decoding method. However, in most practical systems various channel codes, such as Low-Density Parity Check (LDPC) codes [8] or turbo codes [9, 17, 7]. Turbo codes provide a practical way of achieving near-Shannon limit performance by using an iterative decoder that contains two soft-input–soft-output component decoders in series, passing reliability information between them, as shown in Figure 2.

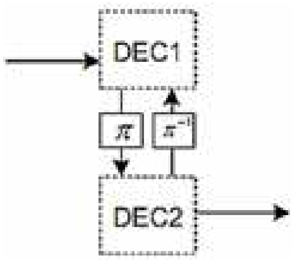

Figure 2: Iterative Decoding in MAP Algorithm

RINGS OF INTEGERS

If the two binary operations '+' and '·' are allowed then a ring can be defined. A ring must have the following conditions:

- Associativity
- Distributivity
- Commutativity under addition

The ring is called a commutative ring if it also has commutativity under multiplication. If the ring has a multiplicative identity 1 then it is called a ring with identity. An example of a ring is the ring of integers $\mathbb{Z}_q$ under modulo-q addition and multiplication, where q is the cardinality of the ring. For example, $\mathbb{Z}_4$is defined as {0, 1, 2, 3}.

It is easy to see that the elements obey the three definitions of a ring. Also, all the elements commute under multiplication and the multiplicative identity element 1 is present, meaning that $\mathbb{Z}_4$ is a commutative ring with identity. Tables 1 and 2 show the addition and multiplication tables respectively of the ring of integers $\mathbb{Z}_4$ = {0, 1, 2, 3}[18].

Table 1: Addition Table for $\mathbb{Z}_4$

+	0	1	2	3
0	0	1	2	3
1	1	2	3	0
2	2	3	0	1
3	3	0	1	2

Table 2: Multiplication Table for $\mathbb{Z}_4$

.	0	1	2	3
0	0	0	0	0
1	0	1	2	3
2	0	2	0	2
3	0	3	2	1

The set of all polynomials with coefficients defined in $\mathbb{Z}_q$ forms a ring under the addition and multiplication operations.

NON-BINARY TURBO TRELLIS CODE MODULATION

Extending binary turbo codes to non-binary turbo codes can be considered. The principle of the non-binary turbo decoding algorithm remains the same. One of the main differences is the trellis diagram associated with a non-binary convolutional code, which has more branches leaving and entering nodes in the trellis, resulting in more paths and higher decoding complexity.

Secondly, an increase in the size of the alphabet means that the reliabilities of these extra symbols must also be considered. The non-binary turbo encoder has the same structure as the binary turbo encoder, with the component encoders being replaced by RSC codes defined over a ring of integers $\mathbb{Z}_M$, where M is the cardinality of the ring.

A $\mathbb{Z}_M$-ring-TTCM encoder system is similar to a classical $\mathbb{Z}_M$-ring-Turbo encoder (parallel concatenation is evident) as shown in Figure 3, but the difference is that, blocks of *n* coded bits are treated as input symbols, and thus, the inter leaver is symbol–oriented, and the component M-ary RSC encoders are trellis encoders–for example, 8–PSK encoder for n = 3 and QAM encoder for n = 4. The final sequence of transmitted symbols is generated by selecting symbols alternately from the two encoders. The non-binary TTCM decoder is also structured analogously to the iterative decoder of a parallel concatenated non-binary turbo-coded system, thus decoding proceeds analogously to standard non-binary turbo decoding.

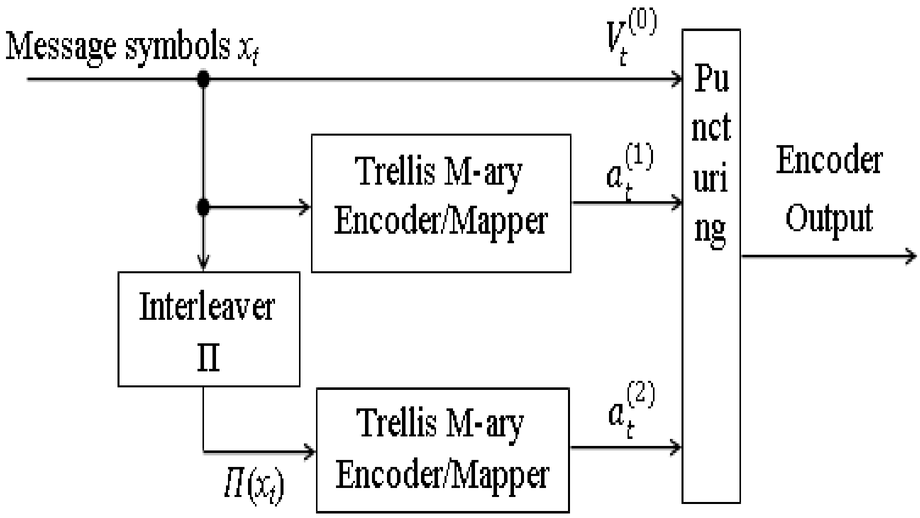

Figure 3: The $\mathbb{Z}_M$-Ring-TTCM Encoder

Where $a_t^{(i)} \in \mathbb{R}$, i = 1, 2, is the mapping of $V_t^{(i)}$ to a selected modulation scheme constellation.

NON-BINARY ITERATIVE TURBO DECODING

Turbo codes are decoded using a method called the Maximum Likelihood Detection or MLD. Filtered signal is fed to the decoders, and the decoders work on the signal amplitude to output a soft “decision”. The form of MLD decoding used by turbo codes is called the Maximum a-posteriori Probability or MAP. The MAP algorithm is used iteratively to improve performance.

The idea of the non-binary turbo decoding process is the same idea of the binary turbo decoding process, in which the extraction of extrinsic information from the output of one decoder and pass it on to the second decoder in order to improve the reliability of the second decoder’s output and vice versa. But, the differences between two decoders aren't in the idea but in mechanisms of decoder parameters design and the decision type as in the following situations:

- The de-mapping procedure of modulated signal into a set ring of integers$\mathbb{Z}_M$.
- Calculation the reliabilities of information bits, parity bits, and interleaved parity bits must be in a ring of integers$\mathbb{Z}_M$.
- Decision method that would be made on the log-likelihood ratios, since the symbols to be decided are defined over a ring of integers $\mathbb{Z}_M$(i.e., 0, 1, 2, . . .M – 1) and not defined over a binary numbers (i.e., 0 and 1).

A general block diagram of the non-binary turbo decoder is shown in Figure 4.

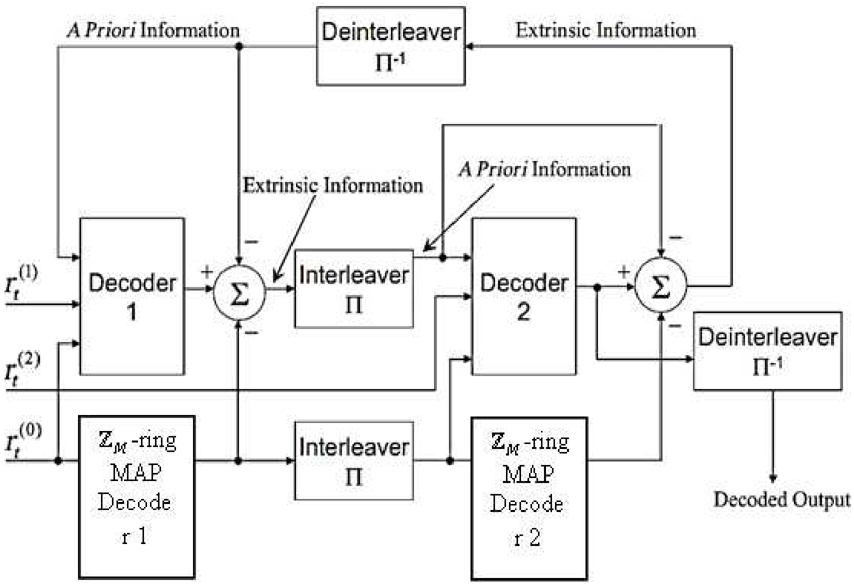

Figure 4: The $\mathbb{Z}_M$-Ring-Turbo Decoder

Where;

- $r_t^{(0)}$is the received information bit.
- $r_t^{(1)}$is the received parity bit from the first RSC encoder.
- $r_t^{(2)}$is the received information bit from the second RSC encoder.

These notations can be defined in more details below:

$$r_t^{(i)} = a_t^{(i)} + \eta_t, \qquad i = 0,1,2. \tag{1}$$

Where $a_t^{(i)} \in \mathbb{R}$, i = 0, 1, 2 is the mapping of $V_t^{(i)}$ to an M–ary modulation scheme constellation and $\mathbb{R}$ is a set of real numbers, since $V_t^{(i)} \in \{0, 1, 2, . . . M\text{-}1\}$, are outputs of the non-binary turbo encoder defined previously and,η_t, is an additive white Gaussian noise sample at time t.

The design procedure of a $\mathbb{Z}_M$-ring-Turbo decoder can be divided into three stages:

- The first stage is to derive the reliability values of the systematic information,$r_t^{(0)}$, the parity bits from encoder 1, $r_t^{(1)}$, and the interleaved parity bits from encoder 2, $r_t^{(2)}$.
- The second stage is to employ the Maximum A Posteriori (MAP) decoding algorithm to perform the symbol-by-symbol, which defined over a ring of integers$\mathbb{Z}_M$, decoding and then decision making.
- The third stage is to derive the mathematical relations that achieve connection between decoder 1 and decoder 2 through iteration cycles.

In non-binary systems, expanding to a ring of integers$\mathbb{Z}_M$, it must be considered the reliabilities of the other symbols too. The multi-dimensional log-likelihood ratios (multi-dimensional LLRs) for an event u being an element in $\mathbb{Z}_M$ are:

$$L^{(1)} = \ln\left(\frac{p(u=1)}{p(u=0)}\right), L^{(2)} = \ln\left(\frac{p(u=2)}{p(u=0)}\right), L^{(3)} = \ln\left(\frac{p(u=3)}{p(u=0)}\right),$$

$$L^{(M-1)} = \ln\left(\frac{p(u=M-1)}{p(u=0)}\right), L^{(M)} = \ln\left(\frac{p(u=M)}{p(u=0)}\right) \quad (2)$$

These multi-dimensional LLRs are used by non-binary turbo decoder as its inputs, and their values depend on the type of the channel and the modulation scheme used.

To derive the multi-dimensional LLRs of a 4-state $\mathbb{Z}_M$-ring-Turbo decoder, with $M \in \{0, 1, 2, 3\}$ and assuming for simplicity, the AWGN channel and 4-ary PAM or 4-ary ASK modulation schemes with constellation points at $\left(\pm\sqrt{E_s/5}\ , \pm 3\sqrt{E_s/5}\right)$ are used, where E_s, is symbol energy.

Since, the values of the non-binary turbo encoder output symbols are $V_t^{(0)}, V_t^{(1)}, V_t^{(2)} \in \{0, 1, 2, 3\}$ and then mapping of $V_t^{(i)}$to the 4-ary ASK constellation,$a_t^{(i)}$,i = 0, 1, 2 is given below:

$$a_t^{(0)} = 2V_t^{(0)} - 3, \quad where\ V_t^{(0)} = 0\ or\ 1\ ,$$

$$a_t^{(1)} = 4V_t^{(1)} - 5, \quad where\ V_t^{(1)} = 1\ or\ 2\ ,$$

$$a_t^{(2)} = -2V_t^{(2)} + 7, \quad where\ V_t^{(2)} = 2\ or\ 3 \quad (3)$$

Thus, the reliabilities of input bits that would be entered to the $\mathbb{Z}_4$-ring-turbo decoder are grouped into three sets:

- First set is to derive the reliability of input bits between -1 and -3.
- Second set is to derive the reliability of input bits between 3 and -3.
- Third set is to derive the reliability of input bits between 1 and -3.

To calculate the reliability of the systematic information bit, $r_t^{(0)}$:

$$L^{(1)}\left(r_t^{(0)} \middle| a_t^{(0)}\right) = ln\left[\frac{p\left(r_t^{(0)} \middle| a_t^{(0)} = -1\right)}{p\left(r_t^{(0)} \middle| a_t^{(0)} = -3\right)}\right] \quad (4)$$

Since, $p\left(r_t^{(0)} \middle| a_t^{(0)}\right)$ represents the conditional probability density function (PDF) for AWGN channel and is given by

$$p(r_t|a_t) = \frac{(1/\sigma\sqrt{2\pi})\,(e^{-(r_t-a_t)^2}/2\sigma^2)}{(1/\sigma\sqrt{2\pi})\left(\sum_{i=\pm1,\pm3}(e^{-(r_t-ia_t)^2}/2\sigma^2)\right)} \quad (5)$$

Where σ^2 , represents the noise variance, for 4-PAM modulation with constellation points at$\left(\pm\sqrt{E_s/5}\ , \pm 3\sqrt{E_s/5}\right)$:

$$p\left(r_t^{(0)} \middle| a_t^{(0)} = -1\right) = \frac{(1/\sigma\sqrt{2\pi})\,(e^{-(r_t^{(0)}+\sqrt{E_S/5})^2}/2\sigma^2)}{(1/\sigma\sqrt{2\pi})\left(\sum_{i=\pm1,\pm3}(e^{-(r_t^{(0)}+i\sqrt{E_S/5})^2}/2\sigma^2)\right)}, \text{ and}$$

$$p\left(r_t^{(0)} \middle| a_t^{(0)} = -3\right) = \frac{(1/\sigma\sqrt{2\pi})\,(e^{-(r_t^{(0)}+3\sqrt{E_S/5})^2}/2\sigma^2)}{(1/\sigma\sqrt{2\pi})\left(\sum_{i=\pm1,\pm3}(e^{-(r_t^{(0)}+i\sqrt{E_S/5})^2}/2\sigma^2)\right)}, \text{ then}$$

$$L^{(1)}\left(r_t^{(0)}\middle|a_t^{(0)}\right) = ln\left[e^{\frac{-\left(r_t^{(0)}+\sqrt{E_S/5}\right)^2+\left(r_t^{(0)}+3\sqrt{E_S/5}\right)^2}{2\sigma^2}}\right], \text{Let } 2\sigma^2 = N_o$$

$$L^{(1)}\left(r_t^{(0)}\middle|a_t^{(0)}\right) = (4/5)\left(\sqrt{E_s}/N_o\right)r_t^{(0)} + (8/5)(E_s/N_o) \quad (6)$$

Thus, each one of the systematic information bit, $r_t^{(0)}$, the parity bit from encoder 1,$r_t^{(1)}$ and the interleaved parity bit from encoder 2,$r_t^{(2)}$, has three reliability values, respectively, as shown below in system of equations:

$$L^{(i)}\left(r_t^{(0)}\middle|a_t^{(0)}\right) = (4/5)\left(\sqrt{E_s}/N_o\right)r_t^{(0)} + (8/5)(E_s/N_o),$$

$$L^{(i)}\left(r_t^{(1)}\middle|a_t^{(1)}\right) = (12/\sqrt{5})\left(\sqrt{E_s}/N_o\right)r_t^{(1)},) \quad (7)$$

$$L^{(i)}\left(r_t^{(2)}\middle|a_t^{(2)}\right) = (8/\sqrt{5})\left(\sqrt{E_s}/N_o\right)r_t^{(2)} + (8/5)(E_s/N_o).$$

Where i = 1, 2, 3.

The non-binary turbo decoders employed multidimensional MAP algorithm. Since the posterior probabilities from each decoder can be defined in the following cases:

- **Case 1:** The decision between (0&1), then posterior probabilities are

  $P\left(a_t^{(0)} = -3\middle|r\right)$ and $P\left(a_t^{(0)} = -1\middle|r\right)$, where r is the received vector.

- **Case 2:** The decision between (0&2), then posterior probabilities are

  $P\left(a_t^{(0)} = -3\middle|r\right)$ and $P\left(a_t^{(0)} = +3\middle|r\right)$.

- **Case 3:** The decision between (0&3), then posterior probabilities are

  $P\left(a_t^{(0)} = -3\middle|r\right)$ and $P\left(a_t^{(0)} = +1\middle|r\right)$.

The prior information into decoder 1 is the deinter leaved extrinsic information from decoder 2, as illustrated below:

$$\left\{L_1^{(1)}\left(a_t^{(0)}\right), L_1^{(2)}\left(a_t^{(0)}\right), L_1^{(3)}\left(a_t^{(0)}\right)\right\} = \left\{L_{e2}^{(1)}\left(\prod^{-1}\left(a_t^{(0)}\right)\right), L_{e2}^{(2)}\left(\prod^{-1}\left(a_t^{(0)}\right)\right), L_{e2}^{(3)}\left(\prod^{-1}\left(a_t^{(0)}\right)\right)\right\}$$

Therefore, the extrinsic information from decoder 1 is given by

$$L_{e1}^{(1)}\left(a_t^{(0)}\right) = L_1^{(1)}\left(a_t^{(0)}\middle|r\right) - L_1^{(1)}\left(a_t^{(0)}\right) - L^{(1)}\left(r_t^{(0)}\middle|a_t^{(0)}\right)$$

$$L_{e1}^{(2)}\left(a_t^{(0)}\right) = L_1^{(2)}\left(a_t^{(0)}\middle|r\right) - L_1^{(2)}\left(a_t^{(0)}\right) - L^{(2)}\left(r_t^{(0)}\middle|a_t^{(0)}\right) \quad (8)$$

$$L_{e1}^{(3)}\left(a_t^{(0)}\right) = L_1^{(3)}\left(a_t^{(0)}\middle|r\right) - L_1^{(3)}\left(a_t^{(0)}\right) - L^{(3)}\left(r_t^{(0)}\middle|a_t^{(0)}\right)$$

Similarly, the extrinsic information from decoder 2 is:

$$L_{e2}^{(1)}\left(a_t^{(0)}\right) = L_2^{(1)}\left(a_t^{(0)}\middle|r\right) - L_2^{(1)}\left(a_t^{(0)}\right) - L_2^{(1)}\left(\prod\left(r_t^{(0)}\middle|a_t^{(0)}\right)\right)$$

$$L_{e2}^{(2)}\left(a_t^{(0)}\right) = L_2^{(2)}\left(a_t^{(0)}\middle|r\right) - L_2^{(2)}\left(a_t^{(0)}\right) - L_2^{(2)}\left(\prod\left(r_t^{(0)}\middle|a_t^{(0)}\right)\right) \quad (9)$$

$$L_{e2}^{(3)}\left(a_t^{(0)}\right) = L_2^{(3)}\left(a_t^{(0)}\middle|r\right) - L_2^{(3)}\left(a_t^{(0)}\right) - L_2^{(3)}\left(\prod\left(r_t^{(0)}\middle|a_t^{(0)}\right)\right)$$

A hard decision is made on the multi-dimensional LLRs from the deinterleaved output of decoder 2 according to the following rule:

$$\text{If} \quad \begin{cases} sign\left(L^{(i)}\left(a_t^{(0)}\middle|r\right)\right) < 0, & a_t^{(0)} = 0 \\ sign\left(L^{(i)}\left(a_t^{(0)}\middle|r\right)\right) \geq 0, & a_t^{(0)} = i, \end{cases} \qquad (10)$$

Where $i = 1, 2, \ldots, M - 1$.

Hence, there are $M - 1$ candidate values for the decoded symbol. The most likely element is determined by comparing each $L^{(i)}\left(a_t^{(0)}\middle|r\right)$and choosing the LLR with the largest magnitude (the highest reliability).

SIMULATION RESULTS

The performances of the $\mathbb{Z}_4$-ring-TTCM-based 3-dimensional MAP decoding algorithm communicating over AWGN channel is presented. The obtained results are discussed and compared with some related works. The flow chart of the $\mathbb{Z}_4$-ring-TTCM decoder with adaptive control is depicted in Figure 5.

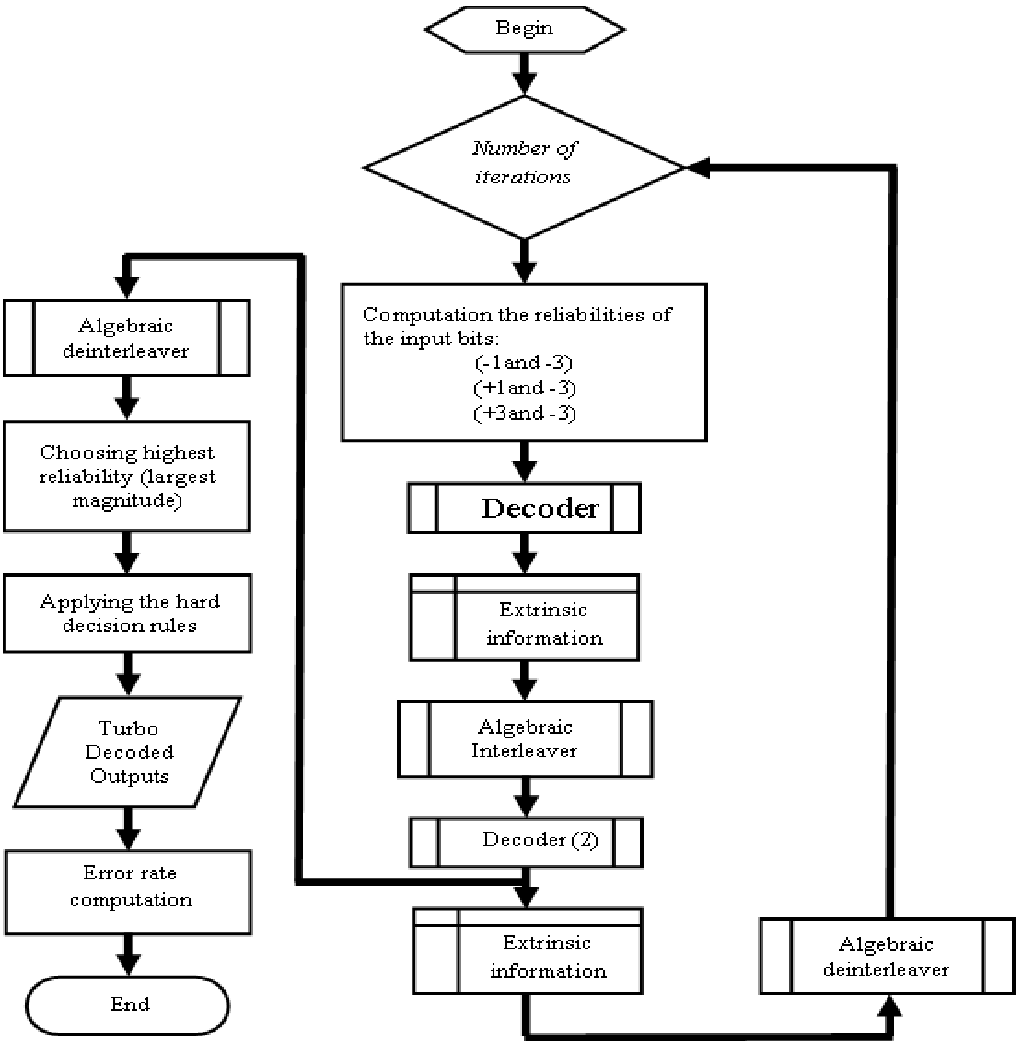

Figure 5: Flow Chart of the $\mathbb{Z}_4$-Ring-TTCM Decoder Algorithm

The $\mathbb{Z}_4$-Ring-TCM encoder-modulator system used PAM modulator. The scatter plot of constellation points for the $\mathbb{Z}_4$-Ring-TTCM encoder-modulator-based PAM scheme is shown in Figure 6.

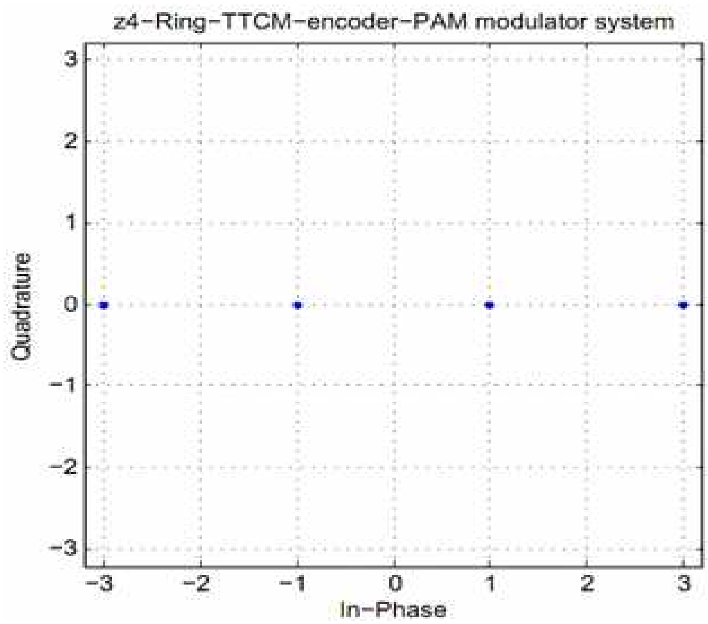

Figure 6: The Scatter Plot of Constellation Points for the $\mathbb{Z}_4$-Ring-TTCM Encoder-Modulator-Based PAM Modulator

The performance of the $\mathbb{Z}_4$-Ring-TTCM-PAMscheme-based 3-dimensional MAP algorithm is considered by evaluating the bit error rate (BER) versus the ratio(E_b/N_0). The simulation result of a non-binary $\mathbb{Z}_4$-Turbo convolutional system is shown in Figure 7, where PAM modulation scheme is used. Figure 8 shows the performance of the $\mathbb{Z}_4$-Ring-TTCM-PAM scheme-based 3-dimensional MAP algorithm with different number of iterations (T).

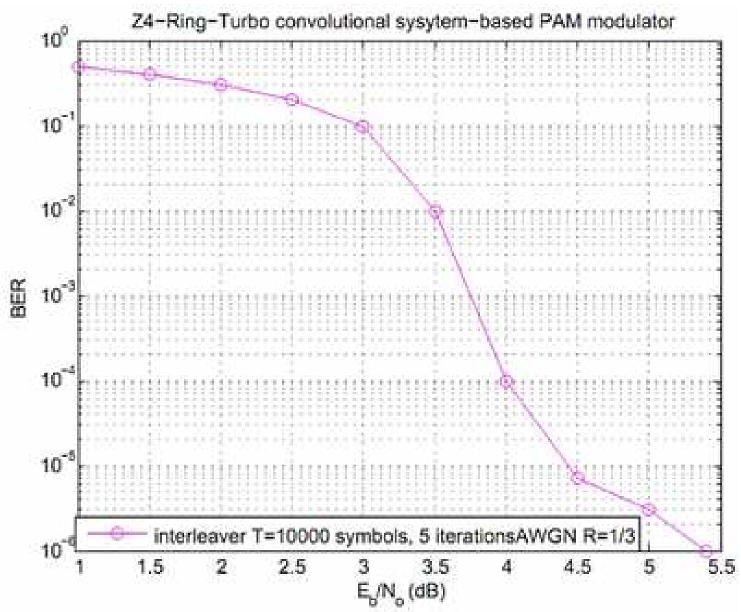

Figure 7: The Performance of the $\mathbb{Z}_4$-Ring-TC System-Based PAM Modulator

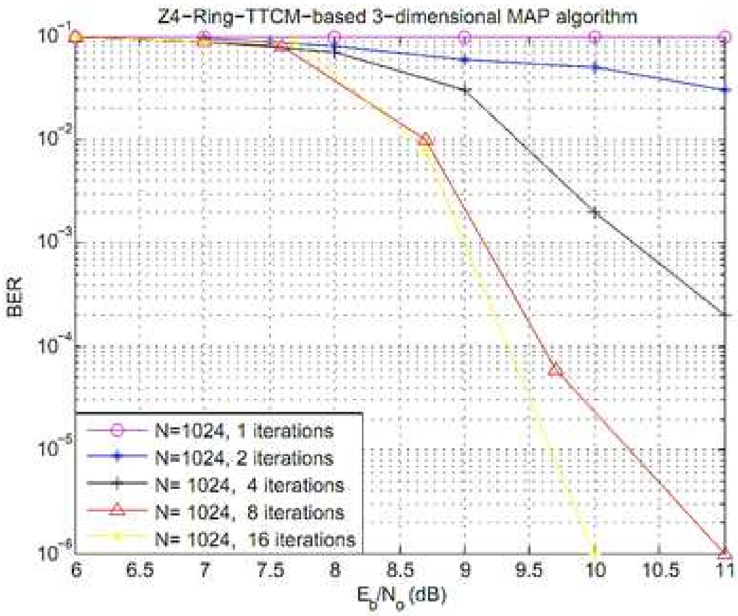

Figure 8: The Performance of the $\mathbb{Z}_4$-Ring-TTCM System-Based 3-Dimensional MAP Algorithm

The complexity of the $\mathbb{Z}_4$-Ring-TTCM scheme-base 3-dimensional decoding algorithm may be calculated and taken into account.

The total estimated complexity of the decoding algorithm per symbol-based codeword length (T) in one iteration, in terms of additions and subtructions, to be carried out is equal to: (2700 operations) for (T = 1024 symbols), but the complexity of the $\mathbb{Z}_4$-Ring-TTCM scheme-based chaos technique is equal to: (2712 operations) for (T = 1024 symbols), and the complexity of the binary (0-1) test algorithm is given by:

$$comp\{(0-1) test\ algorithm\} = 10[\sum_{i=1}^{T}(12)i + 10T^2 + 13T] \quad (11)$$

A comparision between the binary TTCM-QPSK scheme [9] and the proposed $\mathbb{Z}_4$-Ring-TTCM schemes for different number of iterations is given in Table 3.

Table 3: Complexity Comparision of Binary and Non-Binary Schemes

CM Scheme	Code Rate	Data Bits	Iterations	Code Word Length	Total Complexity	Modem
BTTCM	1/2	1	**1**	1024	**300**	QPSK
$\mathbb{Z}_4$-RTTCM	1/2	1	**1**	1024	**2700**	4-PAM
BTTCM	1/2	1	**4**	1024	**1600**	QPSK
Z4-RTTCM	1/2	1	**4**	1024	**10800**	4-PAM
BTTCM	1/2	1	**16**	1024	**4800**	QPSK
Z4-RTTCM	1/2	1	**16**	1024	**43200**	4-PAM

CONCLUSIONS AND FUTURE WORKS

The use of non-binary TTCM codes led to reduction in the effective input block length, since each *m* bits of binary information correspond to one non-binary symbol for $q = 2^m$, and thus non-binary system can be used with high number of symbols. Non-binary TTCM scheme that have modulation order (M) can achieve an error performance similar to that of binary schemes that have higher order (M), and this is the reason of achieving good performance by non-binary systems over binary systems.

Non-binary turbo decoding was achieved by introducing an array of LLR values for each non-zero element in the ring, instead of just one in binary decoding. The drawbacks of non-binary Turbo codes are; more branching leaving each state of trellis structure, non-binary symbols and LLR values, and more computations complexity that need more storage memory.

In non-binary TTCM codes, the needed interleaver size is shorter than that of the binary TTCM codes which improve system performance, since every one non-binary symbol corresponds to *m* binary bits. Non-binary TTCM code has better performance than binary TTCM code in low SNR.

A future work for this work is to design a chaotic interleaver to use instead of the algebraic interleaver in the turbo decoder scheme, since, the purpose of the chaotic interleaver is to offer each encoder an uncorrelated or a "random" version of the information, resulting in parity bits from each RSC that are independent. How "independent" these parity bits are, is essentially a function of the type and length/depth of the interleaver.

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