Adaptive Control on Transient Chaos of Non-Binary TTCM Decoder-assisted $G_2$ STBC-OFDM for Next Generation

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Abstract— This paper presents the channel coding assisted STBC-OFDM systems, and employs the Coded Modulation techniques (CM), since the signal bandwidth available for wireless communications is limited. The paper employs chaos technique at the decoding stage of the Non-binary TTCM decoder, since the turbo decoding algorithm can be viewed as a high-dimensional dynamical nonlinear system. A simple technique to control transient chaos of turbo decoding algorithm is devised. This paper deals with the MIMO-OFDM technique that candidate with the fourth generation (4G) of the wireless communication systems, this technique can provide high data rate transmission without increasing transmit power and expanding bandwidth, also it can efficiently use space resources and has a bright future. The analysis of non-linear discrete deterministic Non-binary TTCM decoder used the Binary (0-1) test for chaos to distinguish between regular and chaotic dynamics. The most powerful aspect of the method is that it is independent of the nature of the vector field (or data) under consideration. The simulation results show that the performance of the TTCM decoding algorithm-based chaos technique outperforms the binary and non-binary decoding methods and suitable to deal with error control coding of the STBC-OFDM schemes.

Index Terms— Turbo codes, TTCM, non-binary error correcting codes, Rings of integers, MIMO, OFDM MIMO-OFDM, STBC, 4G, chaos techniques, nonlinear phenomena of dynamic systems.

I. INTRODUCTION

The fourth generation of wireless communications refers to a collection of technologies and standards that will find their way into a range of new ubiquitous computing and connections systems. 4G offers the promise of allowing users to connect to the Internet and one another through a variety of devices and standards anytime, anywhere, and at a wide range of speeds, from narrowband to broadband [1, 2]. The purposes for which 4G is introduced among the previous generations are due to many factors, including the computational capability and power constraints of the mobile devices, the available bandwidth and transmission efficiency of the wireless network, the quality of service (QoS) support of the network protocols, the universal access capability of the communication system infrastructure and the compression and error control efficiency of video and graphics data [3].

A MIMO system is capable of exploiting transmitter and receiver diversity, hence maintaining reliable communications. The employment of multiple antennas constitutes an effective way of achieving an increased capacity. The classic approach is to use multiple-receiver antennas and exploit Maximum Ratio Combining (MRC) of the received signals for the sake of improving the system’s performance [4, 5]. Alamouti [6] introduced an attractive scheme, which uses two transmitters in conjunction with an arbitrary number of receivers for communications in non-dispersive Rayleigh fading channels. Tarokh et al. [7, 8] generalized Alamouti’s scheme to an arbitrary number of transmitters. These schemes introduced Space–Time Block Codes (STBCs), which show remarkable encoding and decoding simplicity, while achieving a good performance.

To overcome a multipath-fading environment with low complexity and to achieve wireless broadband multimedia communication systems (WBMCS), the orthogonal frequency-division multiplexing (OFDM) transmission scheme is employed [9]. OFDM is one of the applications of a parallel-data-transmission scheme, which reduces the influence of multipath fading and makes complex equalizers unnecessary.

A generic MIMO-OFDM system employing K orthogonal frequency-domain subcarriers and having mt and nr transmit and receive antennas, respectively. Firstly, the OFDM modulation technique is capable of coping with the highly frequency-selective, time-variant channel characteristics associated with mobile wireless communication channels, while possessing a high grade of structural flexibility for exploiting the beneficial properties of MIMO.
architectures. The family of space–time signal processing methods, which allow for the efficient implementation of communication systems employing MIMO architectures, is commonly referred to as smart antennas. Advances in coding, such as turbo [10] and low density parity check codes [11], made it feasible to approach the Shannon capacity limit [12] 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 [13, 14, 15]. Further performance gains can be achieved by using non-binary codes in the coded modulation scheme, but with an increase in the decoding complexity [16].

N. Mobini, 2011 [17] proposed a new iterative decoding algorithm for Low-Density Parity-Check (LDPC) codes and used the adaptive scaling factor \(ae^{-\beta}\) to speed up the convergence of the LDPC decoding codes. But there might be other non-linear scaling functions that can perform better. A further search for discovering other alternative scaling functions makes an interesting research topic.

L. Hanzo et al., 2011 [18] presented that the CM-assisted STBC schemes were found to improve significantly the system’s achievable performance. Furthermore, the TTCM-STBC concatenated scheme was observed to give the best performance among all the CM-STBC concatenated schemes. Also, the TTCM-assisted \(G_2\) coded OFDM scheme gives a better performance than the LDPC-assisted \(G_2\) coded OFDM scheme. Furthermore, in the context of the achievable coding gain versus complexity performance, it was found that the TTCM-assisted schemes are capable of achieving higher coding gains in the relatively high-complexity range, than the LDPC-assisted candidate schemes. L. Zachilas et al., 2012 [19] used the 0-1 test for examining the chaotic behavior in dynamical systems, which is a very efficient method for studying highly chaotic dynamic systems and is particularly useful in characterizing the transition from regularity to chaos, since it is easily calculated method, and accurately detects the onset of strong chaos.

II. OFDM, MIMO, AND MIMO-OFDM

Several different diversity modes are used to make radio communications more robust, even with varying channels. These include time diversity (different timeslots and channel coding), frequency diversity (different channels, spread spectrum, and OFDM), and also spatial diversity. Spatial diversity requires the use of multiple antennas at the transmitter or the receiver end. Multiple antenna systems are typically known as Multiple Input, Multiple Output systems (MIMO). OFDM is a low complex technique used to modulate multiple sub-carriers efficiently by using digital signal processing [20, 21, 22, 23, 24]. An important design goal for a multi-carrier transmission scheme based on OFDM in a mobile radio channel is that the channel can be considered as time-invariant during one OFDM symbol and that fading per sub-channel can be considered as flat.

A MIMO system typically consists of \(m\) transmit and \(n\) receive antennas as shown in Fig. 1. By using the same channel, every antenna receives not only the direct components intended for it, but also the indirect components intended for the other antennas. The fading channel between each transmit-receive antenna pair can be modeled as a SISO channel. A time-independent, narrowband channel is assumed. The direct connection from antenna 1 to 1 is specified with \(h_{11}\), etc., while the indirect connection from antenna 1 to 2 is identified as cross component \(h_{21}\), etc. From this is obtained transmission matrix \(H\) with the dimensions \(n \times m\) [25].

\[
H = \begin{bmatrix}
    h_{11} & h_{12} & h_{13} & h_{1m} \\
    h_{21} & h_{22} & h_{23} & h_{2m} \\
    h_{31} & h_{32} & h_{33} & h_{3m} \\
    \vdots & \vdots & \vdots & \vdots \\
    h_{m1} & h_{m2} & h_{m3} & h_{mm}
\end{bmatrix}
\]  

(1)

The following transmission formula results from receive vector \(y\), transmit vector \(x\), and noise \(n\)

\[
y = Hx + n
\]

(2)

The Alamouti’s \(G_2\) STBC system contains two transmitter antennas and one receiver antenna, a generic STBC is defined by an \((n \times p)\)-dimensional transmission matrix \(G\), where the entries of the matrix \(G\) are linear combinations of the \(k\) input symbols \(x_1, x_2, ..., x_k\) and their conjugates. Each symbol \(x_i\) (\(i = 1, ..., k\)) conveys \(b\) original information bits according to the relevant signal constellation that has \(M = 2^b\) constellation points, and hence can be regarded as information symbols. Thus, \((k \times b)\) input bits are conveyed by each \((n \times p)\) block.
The $G_2$ transmission matrix can be derived in the form of:

$$\begin{bmatrix}
X_1 \\
-X_2 \\
X_1
\end{bmatrix}$$

(3)

Since there are $k = 2$ input symbols, namely $x_1$ and $x_2$, the code rate of $G_2$ is $R = k/n = 1$.

Two algorithms are widely used for decoding STBCs. The maximum likelihood (ML) decoding algorithm generates hard-decision outputs, while the Maximum-A-Posteriori (MAP) decoding algorithm is capable of providing soft outputs, which readily lend themselves to channel coding for achieving further performance improvements.

However, with the advent of MIMO-assisted OFDM systems, the above-mentioned three parameters may be simultaneously improved. Initial field tests of broadband wireless MIMO-OFDM communication systems have shown that an increased capacity, coverage and reliability are achievable with the aid of MIMO techniques [14].

A generic MIMO-OFDM system employing $K$ orthogonal frequency-domain subcarriers and having $m_t$ and $n_r$ transmit and receive antennas, respectively. Firstly, the OFDM modulation technique is capable of coping with the highly frequency-selective, time-variant channel characteristics associated with mobile wireless communication channels, while possessing a high grade of structural flexibility for exploiting the beneficial properties of MIMO architectures. The family of space–time signal processing methods, which allow for the efficient implementation of communication systems employing MIMO architectures, is commonly referred to as smart antennas.

The discrete frequency-domain model of the MIMO-OFDM system is illustrated in Fig. 2, may be characterized as a generalization of the Single-Input Single-Output (SISO) case:

$$y_i[n,k] = \sum_{j=1}^{n_r} H_{ij}[n,k]x_j[n,k] + w_i[n,k]$$

(4)

where $n = 0, 1, \ldots$ and $k = 0, \ldots, K-1$ are the OFDM symbol and subcarrier indices, respectively, while $y_i[n,k]$, $x_j[n,k]$ and $w_i[n,k]$ denote the symbol received at the $i$th receive antenna, the symbol transmitted from the $j$th transmit antenna and the Gaussian noise sample encountered at the $i$th receive antenna, respectively. Furthermore, $H_{ij}[n,k]$ represents the complex-valued CTF coefficient associated with the propagation link connecting the $j$th transmit and $i$th receive antennas at the $k$th OFDM subcarrier and time instance $n$. The MIMO-OFDM system model described by (4) can be interpreted as the per-OFDM- subcarrier vector expression of

$$y[n,k] = H[n,k]X[n,k] + W[n,k]$$

(5)
III. CHANNEL-CODED STBC

The MAP algorithm invoked for decoding STBCs can be exploited by concatenated channel decoders for further improving the system’s performance. This paper concatenates on the STBCs with a Turbo Convolutional (TC) code [26, 4]. The STBCs can also be concatenated with a range of other channel codes, such as Convolutional Codes (CCs), Turbo Bose–Chaudhuri–Hocquenghem (TBCH) codes (a class of FEC codes), etc. The best scheme found was the half-rate TC(2,1,4) code in conjunction with the STBC $G_2$. TTCM [27] is a more recent joint coding and modulation scheme which has a structure similar to that of the family of binary turbo codes.

A. NON-BINARY ITERATIVE TURBO DECODING

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, A general block diagram of the non-binary turbo decoder is shown in Fig. 3.

![Fig. 2 Schematic of a generic MIMO-OFDM BLAST-type transceiver](image)

![Fig. 3 The $Z_M$-ring-Turbo decoder](image)
Where:

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

These notations can be defined in more details below:

\[
\begin{align*}
\tau^{(i)}_t &= a^{(i)}_t + \eta_t, \quad i = 0, 1, 2. 
\end{align*}
\]

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

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:

\[
L^{(1)} = \ln \left( \frac{p(u=1)}{p(u=0)} \right), \quad L^{(2)} = \ln \left( \frac{p(u=2)}{p(u=0)} \right), \quad L^{(3)} = \ln \left( \frac{p(u=3)}{p(u=0)} \right), \quad \ldots \ldots \ldots \ldots \\
\ldots \ldots \ldots \ldots, L^{(M-1)} = \ln \left( \frac{p(u=M-1)}{p(u=0)} \right), \quad L^{(M)} = \ln \left( \frac{p(u=M)}{p(u=0)} \right)
\]

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 \( \mathcal{M} \in \{0, 1, 2, 3\} \), and assuming for simplicity, the AWGN channel and 4-ary PAM or 4-ary ASK modulation schemes with constellation points at \( \pm \sqrt{E_s/5}, \pm 3\sqrt{E_s/5} \) are used, where \( E_s \) is symbol energy.

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

\[
\begin{align*}
\mathcal{A}^{(0)}_{t} &= 2V^{(0)}_t - 3, \quad \text{where } V^{(0)}_t = 0 \text{ or } 1, \\
\mathcal{A}^{(1)}_{t} &= 4V^{(1)}_t - 5, \quad \text{where } V^{(1)}_t = 1 \text{ or } 2, \\
\mathcal{A}^{(2)}_{t} &= -2V^{(2)}_t + 7, \quad \text{where } V^{(2)}_t = 2 \text{ or } 3
\end{align*}
\]

Thus, \( a^{(i)}_t \in \{-3, -1, 3, -1\} \), where \( i = 0, 1, 2 \).

To calculate the reliability of the systematic information bit, \( r^{(0)}_t \):

\[
L^{(1)} \left( \rho^{(0)}_t \right) \left( a^{(0)}_t \right) = \ln \left[ \frac{p(r^{(0)}_t | a^{(0)}_t = -1)}{p(r^{(0)}_t | a^{(0)}_t = -3)} \right]
\]

Since, \( p\left(r^{(0)}_t \mid a^{(0)}_t \right) \) represents the conditional probability density function (PDF) for AWGN channel and is given by

\[
p\left(r^{(0)}_t \mid a^{(0)}_t \right) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left( -\frac{(r^{(0)}_t - a^{(0)}_t)^2}{2\sigma^2} \right)
\]

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

\[
p\left(r^{(0)}_t \mid a^{(0)}_t = -1 \right) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left( -\frac{(r^{(0)}_t - a^{(0)}_t)^2}{2\sigma^2} \right)
\]

and

\[
p\left(r^{(0)}_t \mid a^{(0)}_t = -3 \right) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp \left( -\frac{(r^{(0)}_t + 3\sqrt{E_s/5})^2}{2\sigma^2} \right)
\]
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:

\[
L^{(1)}(r_t^{(0)} \mid a_t^{(0)}) = \frac{(4/5)(\sqrt{E_s/N_0})r_t^{(0)} + (8/5)(E_s/N_0)}{\sigma^2} 
\]

Let \( 2\sigma^2 = N_o \)

\[
L^{(1)}(r_t^{(1)} \mid a_t^{(1)}) = \frac{(4/5)(\sqrt{E_s/N_0})r_t^{(1)} + (8/5)(E_s/N_0)}{\sigma^2} 
\]

Thus the output of each decoder, in each decision case is defined by the multi-dimensional LLR:

- **Case 1**: the decision between (0&1);
  \[
  L^{[1]}(a_t^{(0)} \mid r) = \ln \left( \frac{p(a_t^{(0)} = -1 \mid r)}{p(a_t^{(0)} = -3 \mid r)} \right) 
  \]

- **Case 2**: the decision between (0&2);
  \[
  L^{[2]}(a_t^{(0)} \mid r) = \ln \left( \frac{p(a_t^{(0)} = +3 \mid r)}{p(a_t^{(0)} = -3 \mid r)} \right) 
  \]

- **Case 3**: the decision between (0&3);
  \[
  L^{[3]}(a_t^{(0)} \mid r) = \ln \left( \frac{p(a_t^{(0)} = +1 \mid r)}{p(a_t^{(0)} = -3 \mid r)} \right) 
  \]

### IV. TURBO DECODING ALGORITHM AS A DYNAMICAL SYSTEM

The turbo decoder consists of two components; a decoder \( D_1 \) for the convolutional code \( C_1 \) and a decoder \( D_2 \) for the code \( C_2 \). These decoders use the BCJR algorithm to compute the a posteriori probabilities of the information bits. The posterior likelihood ratio of the \( i \)-th information bit is given by\(^{[17]}\)

\[
\frac{\Sigma_{b \in Y_i} p(b \mid c_i)}{\Sigma_{b \in \bar{Y}_i} p(b \mid c_i)} = \frac{\Sigma_{b \in Y_i} p(b) p(\bar{c}_i \mid b) q_0(b)}{\Sigma_{b \in \bar{Y}_i} p(b) p(\bar{c}_i \mid b) q_0(b)} \quad (16)
\]

Where \( \bar{c}_1 \) and \( \bar{c}_2 \) be the channel outputs corresponding to the input sequences \( i, c_1, \) and \( c_2, \) respectively, while, \( p(b \mid \bar{c}_1, \bar{c}_2) \), is the posterior probability density, where \( b \in H, \) and \( H \) be the set of all ordered binary strings of length \( n \).

Assuming that \( p_0, p_1, \) and \( p_2 \) be the normalized densities equivalent to \( p(b \mid \bar{c}_1), p(\bar{c}_1 \mid b), \) and \( p(\bar{c}_2 \mid b), \) respectively. The likelihood ratios of the information bits according to \( q_1 \) equal their extrinsic information and are given by

\[
q_2(b^i) = \frac{q_{21}^i}{q_{22}^i} = \frac{\Sigma_{b \in \bar{Y}_i} p(b \mid i, \bar{c}_2) p(b^i \mid i) q_2(b^i)}{\Sigma_{b \in Y_i} p(b \mid i, \bar{c}_2) p(b^i \mid i) q_2(b^i)} \quad (17)
\]

In the logarithmic domain, equation (6) can be rewritten as

\[
Q_1(b^i) = \pi p_1 P_0 + Q_2(b^i) - (P_0 + Q_2) \quad (18)
\]

For \( i = 1, ..., n. \) Recalling that \( Q_1 \) and \( Q_2 \) are initialized to induce the uniform probability distribution on \( H. \) Therefore,

\[
Q_1^{(i+1)} = \pi p_1 (P_0 + Q_2) - (P_0 + Q_2) \quad (19)
\]

The decoding algorithm iteratively performs the operations indicated by (18) and (19). The equations (18) and (19) may be considered as a discrete-time dynamical system. Consequently, the turbo decoding algorithm is
parameterized by 3n parameters. Hence, in the above formulation, the turbo decoding algorithm is an n-dimensional dynamical system depending on 3n parameters.

A. DESCRIPTION OF THE BINARY (0-1) TEST FOR CHAOS [28]

Recently a new test for determining chaos is introduced Gottwald and Melbourne [28]. In contrast to usual method of computing maximal lyapunov exponent, their method is applied directly to the time series data and does not require phase-space reconstruction. Moreover, the dimension and origin of the dynamical system and the form of the underlying equations are irrelevant. The input is the time series data and the output is 0 or 1, depending on whether the dynamics is non-chaotic or chaotic. Assuming scalar observable \( \phi(j) \), \( j = 1, 2, 3, \ldots \), T a discrete set of measurement data. To test \( \phi(j) \), the following sequence steps is Performed:

I. for \( c \in (\pi, o) \), compute the translation variables

\[
p_c(t) = \sum_{j=1}^{T} \phi(j) \cos jc , \quad q_c(t) = \sum_{j=1}^{T} \phi(j) \sin jc
\]

(21)

for \( t = 1, 2, \ldots T \)

Claim that

- \( p_c(t) \) is bounded if the underlying dynamics is non-chaotic (e.g periodic or quasi periodic).
- \( q_c(t) \) behaves asymptotically like Brownian motion if the underlying dynamics is chaotic.

II. The mean square displacement of the translation variables \( p_c(t) \) and \( q_c(t) \) defined in (1), for several values of \( c \in (\pi, o) \). The mean square displacement is defined by

\[
M_c(t) = \lim_{n \to \infty} \frac{1}{T} \sum_{j=1}^{T} [P_c(j + \epsilon) - P_c(j)]^2 + [Q_c(j + \epsilon) - Q_c(j)]^2
\]

(22)

and smoothing mean square displacement is

\[
M_c(t)_{new} = M_c(t)_{old} - \frac{1 - \cos(nc)}{1 - \sin(nc)} \left( \lim_{T \to \infty} \frac{1}{T} \sum_{j=1}^{T} \phi(j) \right)^2
\]

(23)

Such that \( t << T, t \leq t_{cut} \), where \( t_{cut} < T \). In practice it is find that \( t_{cut} = T/10 \) yields good results.

III. \( M_c(t) \) grows linearly in time the underlying dynamic is chaotic, but it is not chaotic when \( M_c(t) \) is bounded.

IV. The asymptotic growth rate \( K_c \) can be numerically determined by linear regression of \( \log M_c(t) \) versus \( \log (t) \), and is given by

\[
K_c = \lim_{t \to \infty} \frac{\log M_c(t)}{\log t}
\]

(24)

\[
k = \text{median} (K_c)
\]

(25)

Therefore, if:

- \( k \approx 0 \), then the system is non chaotic,
- \( k \approx 1 \), then the system is chaotic.

Figure 4 is shown in Appendix.

V. PROPOSED Z_4-RING-TTCM MODULATION-ASSISTED STBC-OFDM SCHEME

A simple adaptive control mechanism has developed to reduce the long transient behavior in the decoding algorithm. A schematic block diagram of the \( Z_4 \)-ring-TTCM decoder with adaptive control is depicted in Fig. 4, where the control function \( g(\cdot) \) is given by [17]:

\[
g(X_i) = aX_i e^{-\beta |X_i|}
\]

(26)

Where \( X \) is an extrinsic information variable, and parameters \( a, \beta \) are constant selected from the intervals \((0, 1]\) and \([0, +\infty)\), respectively, to optimize the error rate performance of the algorithm. The optimal values of \( a, \beta \) are usually close to the end and the beginning of the corresponding intervals, respectively. The control function is chosen because if \( X_i \) is small, then the attenuation factor in equation (26) is close to 1 (since \( a \) is close to 1 and \( \beta \) is small).

In other words, the control algorithm does nothing. If, however, \( X_i \) is large, then the control algorithm reduces the normalization factor, thereby, attenuating the effect of \( X_i \) on the decoding algorithm. The adaptive control algorithm of Fig. 4 is very simple, and can be easily implemented (both in software and/or in hardware) without significantly increasing the complexity of the decoding algorithm. Fig. 5 shows a schematic of the \( Z_4 \)-ring-TTCM decoder-based chaos technique-assisted \( G_2 \) STBC-OFDM system. The source information bits are first encoded
and modulated by the $\mathbb{Z}_4$-ring-TTCM encoder followed by the space–time encoder, the STBC employed was the $G_2$ code, which invokes two transmitter antennas, and the two space–time-coded samples are mapped to two consecutive OFDM subcarriers and OFDM modulated. The OFDM symbols are then transmitted via the multi-path fading channel, and the received noise-contaminated symbols are forwarded to the OFDM demodulator. The recovered signal is then space–time soft decoded and the soft outputs are fed to the $\mathbb{Z}_4$-ring-TTCM decoder which used the multi-dimensional MAP algorithm for recovering the most likely transmitted information bits.

VI. SIMULATION RESULTS

The schematic design of $\mathbb{Z}_4$-ring-TTCM encoder can be simulated on computer. The $\mathbb{Z}_4$-ring-TTCM encoder passes through 4-state transitions, since at each state two sets of non-binary mathematical operations are used to encode a message, one for the normal turbo code output and the other for the interleaved output. A modulation scheme, pulse amplitude modulation of fourth order, is suitable to modulate the encoded bits with low probability of errors. The simulation results of both $\mathbb{Z}_4$-Ring-TTCM-assisted $G_2$ STBC-OFDM and $\mathbb{Z}_4$-Ring-TTCM-based chaos technique scheme-assisted $G_2$ STBC-OFDM can be shown in Fig. 6. The simulation results of both binary TTCM-QPSK-assisted $G_2$ STBC-OFDM [18] and the $\mathbb{Z}_4$-Ring-TTCM scheme-assisted $G_2$ STBC-OFDM can be shown in Fig. 7 where the code rate of $G_2$ STBC scheme is (1) and code rate of TTCM is (1/2).
The performances of the uncoded BPSK scheme, the $G_2$ STBC scheme, the BTTCM-QPSK scheme-assisted $G_2$ STBC-OFDM system [18], and the $Z_4$-ring-TTCM-PAM scheme-assisted $G_2$ STBC-OFDM system, can be summarized in Table (1), where the coding gains are defined as the $(E_b/N_o)$ difference, expressed in decibels, at BERs of $10^{-5}$ and $10^{-3}$ between the various channel coding assisted STBC-OFDM systems and the uncoded single transmitter system having the same effective throughput. The performance of the best scheme in Table I is (printed in bold), since the performance comparison shows that the $Z_4$-ring-TTCM-PAM scheme-assisted $G_2$ STBC-OFDM and the $Z_4$-ring-TTCM-PAM-based chaos technique-assisted $G_2$ STBC-OFDM outperform the systems [18]. Since, the $Z_4$-ring-TTCM-PAM scheme-assisted $G_2$ STBC-OFDM system is provided that the gains in $(E_b/N_o)$ are (18.60dB) and (35.12 dB) at the BERs of $10^{-3}$ and $10^{-5}$ respectively, and also, the $Z_4$-ring-TTCM-PAM scheme-based chaos technique-assisted $G_2$ STBC-OFDM system is provided that the gains in $(E_b/N_o)$ are (19.19dB) and (34.87 dB) at the BERs of $10^{-3}$ and $10^{-5}$ respectively as shown in Table I.

**Table I: The performance comparison between binary and non-binary CM schemes-assisted $G_2$ STBC-OFDM system.**

<table>
<thead>
<tr>
<th>STBC scheme</th>
<th>CM scheme</th>
<th>CM Code rate</th>
<th>$E_b/N_o$ (dB)</th>
<th>Gain (dB)</th>
<th>Rayleigh fading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoded</td>
<td>---------</td>
<td>1/2</td>
<td>$10^{-3}$</td>
<td>24.11</td>
<td>44.12</td>
</tr>
<tr>
<td>$G_2$</td>
<td>TTCM</td>
<td>1/2</td>
<td>$10^{-3}$</td>
<td>13.93</td>
<td>25.87</td>
</tr>
<tr>
<td>$G_2$ STBC-OFDM</td>
<td>Z4-RTTCM</td>
<td>1/2</td>
<td>$10^{-3}$</td>
<td>7.91</td>
<td>11.82</td>
</tr>
<tr>
<td>$G_2$ STBC-OFDM</td>
<td>Z4-RTTCM</td>
<td>1/2</td>
<td>$10^{-3}$</td>
<td>5.51</td>
<td>9.00</td>
</tr>
<tr>
<td>$G_2$ STBC-OFDM</td>
<td>Based chaos</td>
<td>1/2</td>
<td>$10^{-3}$</td>
<td>4.92</td>
<td>9.25</td>
</tr>
</tbody>
</table>

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 $q = 2m$, 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. The non-binary turbo decoding algorithm can be viewed as a high-dimensional dynamical system parameterized by a large number of parameters. As an application of the chaos theory developed, it has devised a simple technique to control transient chaos of the non-binary turbo decoding algorithm. This results in a faster convergence and a significant gain in terms of BER performance. Binary test for chaos, the 0-1 test is used for testing the extrinsic information of non-binary turbo decoding algorithm, the most powerful aspect of the method, which differs from Lyapunov exponents method, it is independent of the nature of the vector field (or data) under consideration. Non-binary TTCM code has better performance than binary TTCM code in low SNR and is suitable for combining with MIMO-OFDM system.

As a future work related to this work, find other adaptive control functions, since there might be other non-linear scaling functions that can perform better. A further search for discovering other alternative scaling functions makes an interesting research topic, this can be done by repeating apply binary (0-1) test for chaos for each chosen function.

REFERENCES


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Fig. (4): The Non-binary TTCM decoder defined over $\mathbb{Z}_M$ with adaptive control $g(.)$ of the transient chaos.