International Journal of Electrical and Computer Engineering (IJECE)
Vol. 14, No. 5, October 2024, pp. 5263~5273
ISSN: 2088-8708, DOI: 10.11591/ijece.v14i5.pp5263-5273

Dual soft decoding of linear block codes using memetic algorithm

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Article Info

Article history:

Received Dec 23, 2023
Revised Apr 23, 2024
Accepted Jun 9, 2024

Keywords:

Codeword
Decoder
Encoder
Genetic algorithms
Linear block codes
Local search

ABSTRACT

In this article we will approach the soft-decision decoding for the linear block codes, is a kind of decoding algorithms used to decode data to form better original estimated received message, it is considered as a NP-hard problem. In this article we present a new decoder using memetic algorithm such metaheuristic technic operates on the dual code rather than the code itself that aims to find the error caused when sending a codeword calculated from a message of k bits of information, the resulting codeword contains n bits, including the redundancy bits, the efficiency of an error-correcting code is equivalent to the ratio k/n, the rate is belong the interval [0,1]. Hence a good code is the one that ensures a certain error correcting capability at minimum ratio. The results proved that this approach using a combination of genetic algorithm and local search algorithm provides a sufficiently good solution to an optimization problem; the new decoder is applied on linear codes where the structure is given by a parity check matrix.

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1. INTRODUCTION

The major problem of digital communication [1]–[3] is the way to transmit a message from the source to destination over a noise sensitive communication channel without impacting it as much as possible. The error-correcting codes is one of the most used techniques to ameliorate the reliability of data transmitted. In general, the communication system consists of the elements shown in Figure 1, contain the source that transmits a digital message in the form of a series of binary elements to the encoder that divided in two categories, source encoding is used to reduce redundancy in information from the source and the channel encoding consist to introduce redundancy in transmitted signal in order to protect it against noise and interference present on the transmission channel, then come the role of modulation to adapt the spectrum of the signal to the channel on which it will be transmitted. On the receiver side, the demodulation and decoding functions are the respective inverses of the modulation and coding located on the transmitter side. The decoder receives the incoming code via the noisy channel and performs to decode it or preceded to error correction to retrieve the original data. If there are no errors, then it is easy to decode the data by eliminating the redundancy bits, otherwise more complex decoding mechanisms are adopted.

Decoding techniques is composed of two categories, soft and hard decision [4], with the hard decision the received signal is set against a set threshold value, but the soft decision be based on a probability distribution that calculate the likelihood of each received signal. Error correcting codes [5] are divided into 2 classes, block codes: they process each block of information independently of each other, and the convolutional codes [6]: the output of a convolutional encoder depends on current information to be coded and the previous information.

Several work were proposed for improving the soft decision decoding using different ways to form better estimates of the original data sent, these techniques show a good result, we start with approaches using the probabilistic and algebraic methods, such as generalized minimum distance decoding (GMD) [7], chase-2 algorithm [8], ordered statistics decoding (OSD) algorithm [9], and Hartmann Rudolph [10]. Instead of traditional algorithms considered ineffective for solving optimization problems, we introduced metaheuristic and artificial intelligence (AI) methods. Various research was published hinge on genetic algorithms (GA) [11]–[18] ant colony [19], [20], neural network [21], algorithms form on genetic algorithms, and neural network for binary linear codes [22], and Chana *et al.* [23] present a decoding algorithm that aims to make use of the cyclic property exist on the most used linear block codes which are cyclic codes.

Bouzkraoui *et al.* [24] introduces a soft-decision decoding algorithm using memetic algorithm that achieved an efficient result, this paper present a new decoder based also on memetic algorithm but operates on the dual code depending on parity-check matrix instead of the code itself, it aims to detect the error in the received message caused by the noisy channel used to transfer the codeword , this decoder is applied to linear block codes [25], nonbinary or binary codes and noncyclic or cyclic codes, in order to show the efficiency of this decoder, we applied it for QR, Bose-Chaudhuri-Hocquengham (BCH) [26], Reed-Solomon (RS) [27], Reed-Muller (RM) [28] and low-density parity-check (LDPC) [29] codes over a transmission channel (AWGN).

The rest of this paper is organized as follows; section 2 presents the memetic algorithm. Then in section 3, the algorithm proposed is described, after we will process to tune the used parameters and discuss the results of the simulations in section 4. Conclusion in section 5.

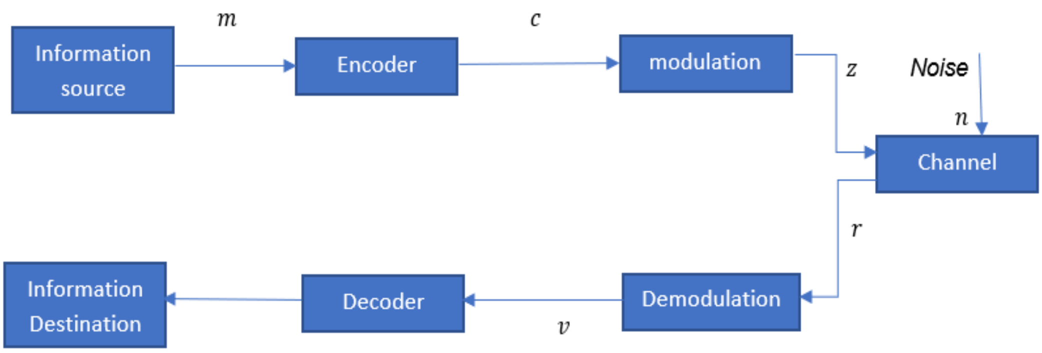

Figure 1. Simplified model communication system

2. MEMETIC ALGORITHM

Memetic algorithm [30], [31], is classified as metaheuristics that aims to solve optimization problems when there is no efficient way to solve them, it composed of a combination of genetic algorithm [32]–[34], and local search algorithm that use the resolution process that genetic algorithm follow and add a local search operator, to start the process it need an initial population, the algorithm follows several steps summarized:

– Generate a random population
– Assess each individual
– Select two parents (individuals) from the population
– Crossing [35] of the two parents in order to generate a new child
– Applied the local search operator on the child
– Update the population and keep the best individuals

3. DUAL SOFT DECISION DECODING USING MEMETIC ALGORITHM

3.1. Proposed decoding algorithm

We consider a linear code of dimension k, length n and minimum distance d noted $C(n,k,d) \subset F_2^n$, the code is described by a generater matric called $G(k \times n)$, the source sent a message noted $m = \{m_i\}_k^1$ that encoded to $c = \{c_i\}_n^1$ called codeword using (1):

$$c = mG \quad (1)$$

We determine H described by $H(n \times (n-k))$ called a parity check matrix, that satisfy $GH^T = 0$ and $\forall\, c \in F_2^n$, c is a codeword <=>

$$cH^T = 0 \quad (2)$$

After the encoding of m and obtain the codeword c, comes the modulation phase using BPSK modulation to get $z = \{z_i\}_n^1$ then via a guassian channel with noise noted $n = \{n_i\}_n^1$, where $z = \{z_i\}_n^1$ and $n = \{n_i\}_n^1$ are independent, $n_i \sim N\,(0, N_0/2\,)$ and N_0 is the noise power spectral density. The received signal defined by $r = \{r_i\}_n^1$ such as $r = z + n$. After the hard decision of $r = \{r_i\}_n^1$ we obtain $v = \{v_i\}_n^1$, the error syndrome $s = \{s_i\}_{n-k}^1$ is presented as (3).

$$S = vH^t \quad (3)$$

If it equal to zero, mean that there is no error and the hard decision signal equal to the codeword sent, otherwise we try to calculate the probability of each possible transmitted message based on the received signal then selects the one with the highest probability named maximum likelihood decoding (MLD) that given by (4).

$$f_{r/z} = \frac{\Lambda}{(\pi N_0)^{n/2}} exp\left(\sum_{i=1}^{n} \frac{-\{r_i - z_i\}^2}{N_0}\right) \quad (4)$$

The MLD can be expressed as a minimum Euclidean distance value before any hard decision.

$$max\,\{f_{r/z}/c \in C\,\} \leftrightarrow min\{\sum_{i=1}^{n}(r_i - z_i)^2 \,/\, c \in C\}$$

$$f(c) = \sum_{i=1}^{n}(r_i - z_i)^2$$

where

$$c = \{c_i\}_n^1 \text{ and } z_i = (-1)^{c_i} \quad (5)$$

In this step we attain the role of decoder that react as follow:

- We apply the hard decision to the received signal $r = \{r_i\}_n^1$ to obtain $v = \{v_i\}_n^1$

$$v_i = \begin{cases} 1 & r_i < 0 \\ 0 & r_i \geq 0 \end{cases} \quad (6)$$

- We proceed to identify the error e that was added by the channel to deduct the sent message using (7),

$$c + e = v \quad (7)$$

Suppose that the matrix is written in (8):

$$H = [AI_{n-k}] \quad (8)$$

and

$$cH^t = 0 \text{ , so } vH^t = (c+e)H^t = cH^t + eH^t = eH^t = S \quad (9)$$

We calculate $S = vH^t$ if $S = 0$ we deduce that not error detected and the received signal is the same sent.

If the syndrome $S \neq 0$ we apply a permutation in decreasing order to the sequences $r = \{r_i\}_n^1$ based on reliability ($|r_i| > |r_{i+1}|$) to get a new sequences $r' = \{r_i'\}_n^1$, noted Π the permutation made on r we applied it to H to obtain H' and z to get $z' = \Pi^{-1}(z)$ and we apply the gaussian elimantion to H' to obtain a systematic matrix.

We consider that the k positions represent the reliable information of the received signal $r = \{r_i\}_n^1$, using that the error will be writen as follow $e = (e_I, e_J)$ where I is the reliable information and J represent the unreliable components.

Then (9) will be created in this form:

$$(e_I, e_J)\begin{pmatrix} A^t \\ I_{n-k} \end{pmatrix} = S \Leftrightarrow e_J = e_I A^t + S \quad (10)$$

After we proceed to deduct the components of $e_J = \{e\}_n^{k+1}$ by generating e_I using (10).

- Apply the memetic algorithm and use (10) to get the best error e_{best} from the best member of the last generation this algorithm will be detailed later.

The codeword obtained $c' = v + e_{best}$ is related to the H' matrix, therefore our estimated transmitted codeword is $\hat{c} = \Pi^{-1}(c')$. The steps followed by the memetic decoder are resumed in the schema illustrated in Figure 2. Noted that N_i is the population size, N_e, the number of elite members, N_g the number of generations, LN_i the number of generations of local search, pc is the crossover rate and pm the mutation rate.

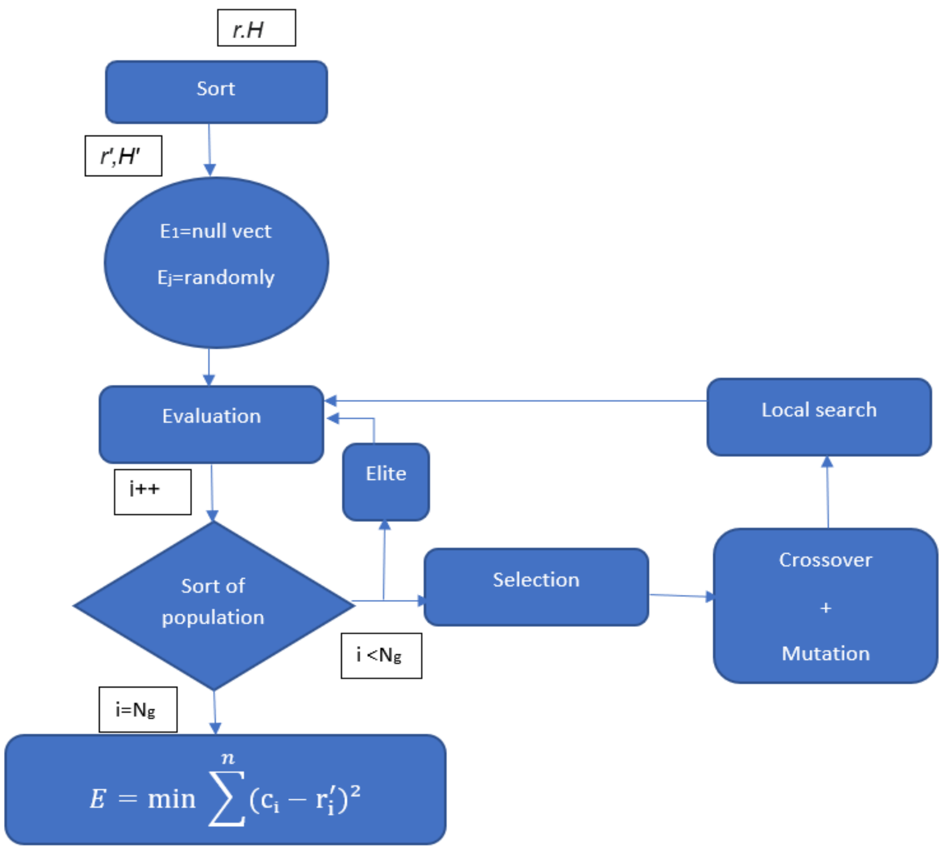

Figure 2. Structure of the proposed algorithm

Step 1: Applied a permutation π for r in decreasing order for r to obtain ($r' = \pi(r)$), and for H to get a new check matrix H'

Step 2: Generate a N_i vectors of k bits represent the initial population (the individual represents the systematic part of the error).

Substep 2.1: We fixed a zero vector E_1 of the first population.

Substep 2.2: Generate randomly a $N_i - 1$ members E_j such as $2 \leq j \leq N_i$

Step 3: For i from 1 to N_g

Substep 3.1: we calculate for each individual the fitness.

We construct the error E like $E = (E', E'')$ using (10), where the chosen individual is E' composed of k bits.
Our fitness function represented as the squared Euclidean distance of the permuted received word and the related encoded individual

$$f(E) = \sum_{i=1}^{n} (\mathrm{c_i} - \mathrm{r'_i})^2$$

Substep 3.2: we insert in next one the best members N_e (elite) of this generation.
Substep 3.3: Generate in next substeps the $N_\mathrm{i} - N_\mathrm{e}$ members of the next generation.
Substep 3.3.1: Comes the selection operation to identify the best parents $({E'}^{(1)}, {E'}^{(2)})$ using the random method on which we applied the reproduction operators.
Sub-substep 3.3.2: E'_j is a new vector child created, is composed of k bits. $Rand_1$ is a random value which varies between 0 and 1 we generate at each occurrence. The crossover operator is defined as:
if $Rand_1 \prec p_c$, the i^{th} bit of child (E'_j), such as $N_\mathrm{e} + 1 \le j \le N_\mathrm{i}$ and $1 \le i \le k$ is given by:

$$E'_{j\mathrm{i}} = \begin{cases} E_i'^{(1)} & if\ E_i'^{(1)} = E_i'^{(2)} \\ Otherwise & \begin{cases} E_i'^{(1)}\ if\ rand_2 \prec p \\ E_i'^{(2)}\ otherwise \end{cases} \end{cases}$$

where:

$$p = \begin{cases} \dfrac{1}{1 + e^{-4\, r'_j/N_0}} & if\quad {E'}^{(1)} = 0\,, {E'}^{(2)} = 1 \\ \dfrac{e^{-4 r'_j/N_0}}{1 + e^{-4\, r'_j/N_0}} & if\quad {E'}^{(1)} = 1\,, {E'}^{(2)} = 0 \end{cases}$$

if the i^{th} bit of the parents is not equal, then for greater positive values of r'_j, the function $\frac{1}{1+e^{-4\, r'_j/N_0}}$ converges to 1. So, the i^{th} bit of the child has a high probability to equal 0.
if $Rand_1 \ge p_c$ no crossover:

$$E'_j = \begin{cases} {E'}^{(1)} & if\ rand < 0.5 \\ {E'}^{(2)} & Otherwise \end{cases}$$

Sub-substep 3.3.3: after the crossover the bits $E'_{j\mathrm{i}}$ are muted with p_m:

$$E'_{j\mathrm{i}} \leftarrow 1 - E'_{j\mathrm{i}} \quad if \quad Rand_3 < p_m$$

Sub-substep 3.3.4: apply local search algorithm:

$Repeat$
$Choose\ E' \in V\ (E) (such\ that\ f(E')\ is\ minimal)$
$E \leftarrow E'$
$until\ (counter\ >\ LN_g)$
$V(E)\ (the\ set\ of\ binary\ strings\ at\ a\ distance\ 1\ of\ E\ \text{“}we\ change\ only\ 1\ bit\text{”})$

3.2. Complexity analysis

Table 1 illustrate the complexity of the algorithms cited in this article, the proposed decoder complexity is polynomial based on N_i, N_g, k, n and LN_g , the same for DDGA [12], GADEC [14], and AutDAG [16], algorithms but in terms of N_i, N_g, k, n ,for SDGA [11] and chase-2, are incremented exponentially with t that represent the error correction capability of a linear bloc code, concerning OSD and Chana [23] the complexity increase with m the order of OSD and p is the number of tests sequence, finally CGAD [13] that also polynomial in T_c presented as being the average number of generations.

Table 1. Complexity of the proposed and the competitors' decoders

Algorithm	Complexity
Chase-2	$O(2^t n^2 \log n)$
OSD-m	$O(n^{m+1})$
GADEC	$0(N_i N_g[kn + log(N_i)])$
DDGA	$0(N_i N_g[k(n-k) + log(N_i)])$
AutDAG	$0(N_i N_g kn)$
SDGA	$0(2^t(N_i N_g[kn^2 + kn + log(N_i)]))$
CGAD	$O(T_c k(n-k))$
Chana dec	$O(2^{P+1}(k\, log(n)\, [n + log(n-k)]))$
Proposed Algorithm	$0(N_i N_g[LN_g(n-k)k + log(N_i)])$

Note: Let k is the code dimension, n the length of the code, N_i is the population size, N_g the number of generations and LN_g the number of generations of local search.

4. SIMULATION RESULTS AND DISCUSSION
4.1. Tuning the parameters

In order to obtain more performance results, we proceeded to tune the different parameters used by our proposed algorithm. Below the simulations made for this purpose, the performances are given in bit error rate (BER). From this Figure 3 we notice that *Ng* achieve the best value when *Ng*=10. We observe from Figure 4 that the BER decrease until it reaches the optimal value 60, and then the value comes back incremented when we use a big population. We conclude that we do not need a huge number of populations to obtain efficient results. From Figure 5, when *LNg*=5 the value of BER reach the worst performance. We observe from Figure 6 that Pc increase in the interval [0.1,0.5] and after the value decrease until it achieves the optimal value estimated to 0.97. Figure 7 reveal that the best choice of this parameter is 0.03. The results obtained when tuning the parameters are summarized in Table 2.

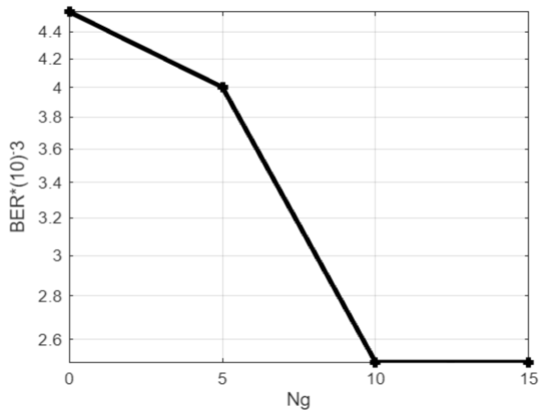

Figure 3. The BER progress with the *Ng* parameter

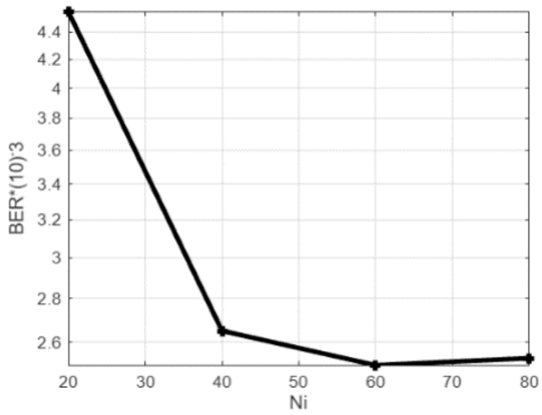

Figure 4. The BER progress with the N_i parameter

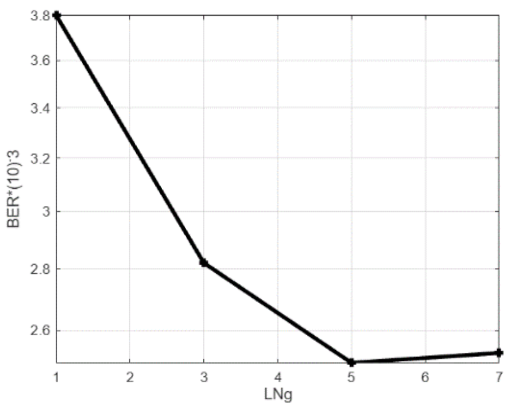

Figure 5. The BER progress with the LN_g parameter

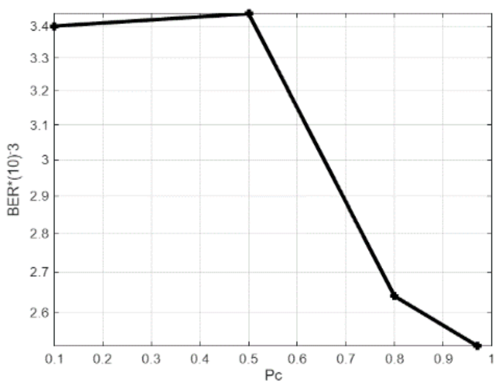

Figure 6. The BER progress with the p_c parameter

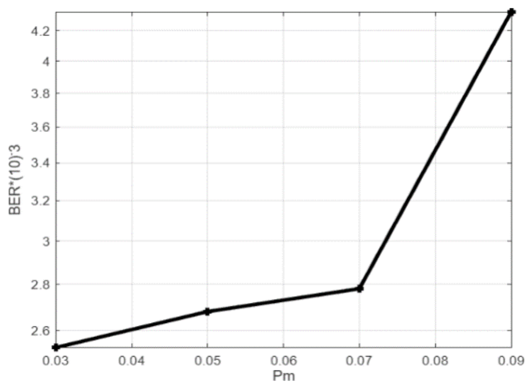

Figure 7. The BER progress with the P_m parameter

Table 2. Parameters

Parameter	Value
Crossover rate ($\mathbf{p_c}$)	0.97
Mutation rate ($\boldsymbol{p_m}$)	0.03
Generation number of generation $\boldsymbol{N_g}$	10
elite number (Ne)	1
Population size ($\boldsymbol{N_i}$)	60
Generation number of local search ($\boldsymbol{LN_g}$)	5
Channel used	AWGN
Modulation operation	BPSK
Minimum number of bit errors	200
Minimum number of blocks	1,000

4.2. Comparison between the proposed decoder and the previous works

In the current section, we will simulate our work by using different codes and then we move to compare our proposed algorithm with the other competing algorithms. The simulations are carried out based on the parameters already cited in Table 2. The performances are presented in bit error rate (BER) as a function of signal to noise ratio (SNR). The SNR or signal to noise ratio represents the radio of signal power and the noise, it measures how the signal is clean, and BER is described by the number of bit errors divided by the quantity of transferred bits. The curve shows the relationship between the SNR and the bit error rate, or how SNR affects the bit error rate typically demonstrating that as the SNR increases, the bit error rate decreases, this curve is important in communication systems as it helps in determining the minimum required SNR for reliable communication, and it is a key factor in designing and evaluating communication system efficiency.

Figure 8 reveal the performance of OSD-1, the proposed algorithm, GADEC and chase-2 decoders using BCH (63,51,5) code, we observe that the proposed decoder is more efficient than Chase2 and OSD-1, at 10^{-5} we gain 0.9 dB over chase-2, but for GADEC it presents almost the same result as our decoder that reach 6×10^{-6} at SNR=5 dB. Figure 9 compares the proposed decoder with cGA-M [17] and cGA-HSP [17], we see that our approach performs widely the other decoders, at 10^{-3} and 10^{-4} we gain respectively almost 0.74 dB over both algorithms and approximately 1 dB over cGA-M. For BCH (63,45,7), our decoder present in Figure 10 a good performance against SDGA, AutDAG, Chana algorithms, at 10^{-5} we gain 0.25 dB over AutDAG, 1 dB over SDGA and 0.6 dB over chana.

For BCH (63,51,5) presented in Figure 11, the proposed algorithm obtains the same performance as GADEC and DDGA at 10^{-5} with 5.5 as a value, but it is better CGAD, and chase-2 algorithms as illustrated in Figure 11. From Figure 12, we conclude that our decoder is comparable with OSD-3 and performs AutDAG, Chana algorithm for QR (71,36,11). Figure 13 compares our approach with chase-2, SDGA, and DDGA algorithms using RS (15,7,9), at 10^{-5} we gain 2 dB over Chase-2 and SDGA, and 0.6 dB against DDGA. For RS (15,7,9), the simulation shown in Figure 14 displays that our decoder performs widely the other algorithms, at 10^{-4} we gain approximately 2 dB against cGA-HSP, 2.6 dB compared to CGAD and 2.3 dB over cGA-M. The Figure 15 compares the proposed algorithm to SDGA decoder for RM (32,16,8) code, it shows that the first one is better than the second, at 10^{-5} we gain 0.7 dB. From the Figure 16, we observe that our algorithm outperforms Sum-Product, GAMD [18] for LDPC (60,30), it achieves $2 * 10^{-5}$ at SNR=5 dB. Based on this figure we notice that our decoder outperforms the majority of algorithms proposed on the previous words cited in this section.

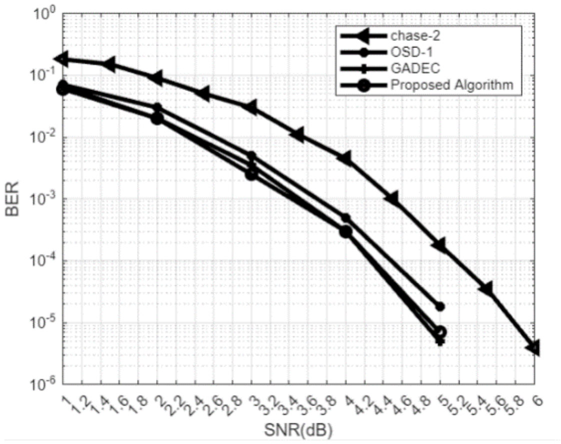

Figure 8. Performances of OSD-1, the proposed algorithm, GADEC and chase-2 using BCH (63,51,5)

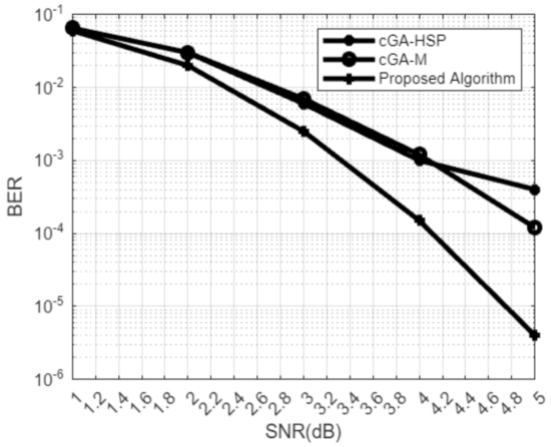

Figure 9. Performances of the proposed algorithm, cGA-M and cGA-HSP using BCH (63,45,7)

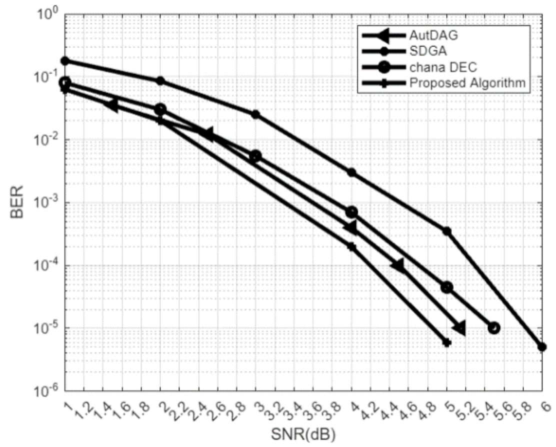

Figure 10. Performances of the proposed algorithm, AutDAG, SDGA and chana using BCH (63,45,7)

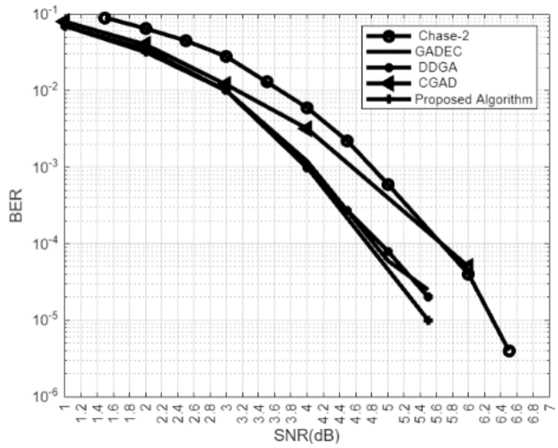

Figure 11. Performances of the proposed algorithm, GADEC, Chase-2, CGAD and DDGA using BCH (63,51,5)

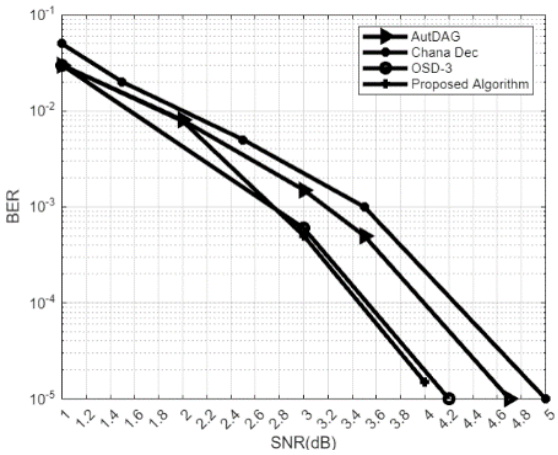

Figure 12. Performances of OSD3, AutDAG, the proposed algorithm, and Chana Dec using QR (71,36,11)

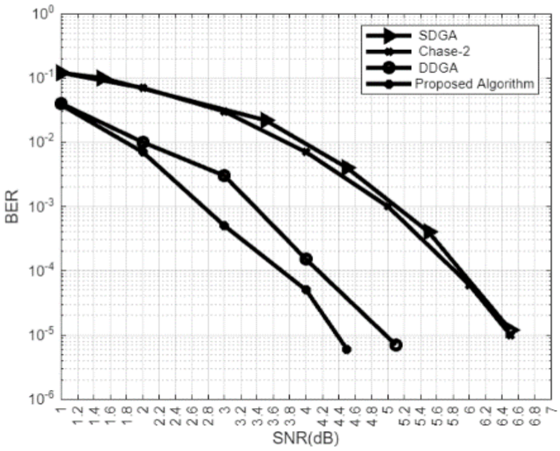

Figure 13. Performances of Chase-2, SDGA and DDGA and the proposed algorithm using RS (15,7,9)

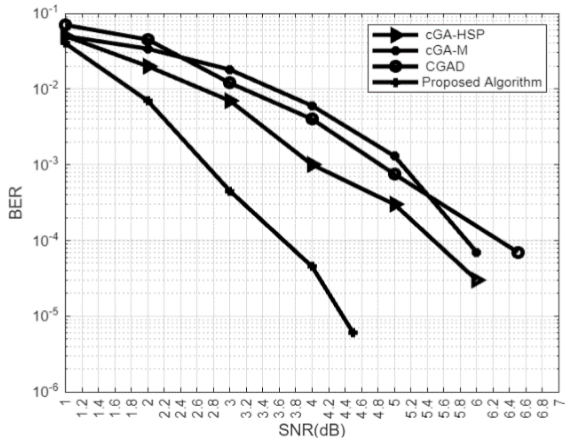

Figure 14. Performances of the proposed algorithm, CGAD, cGA-M and cGA-HSP using RS (15,7,9)

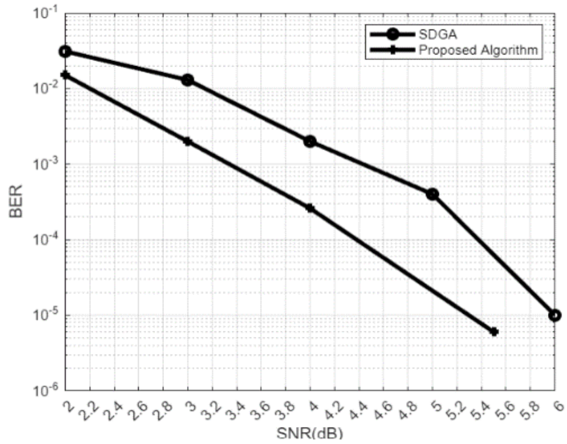

Figure 15. Performances of the proposed algorithm and SDGA using RM (32,16,8)

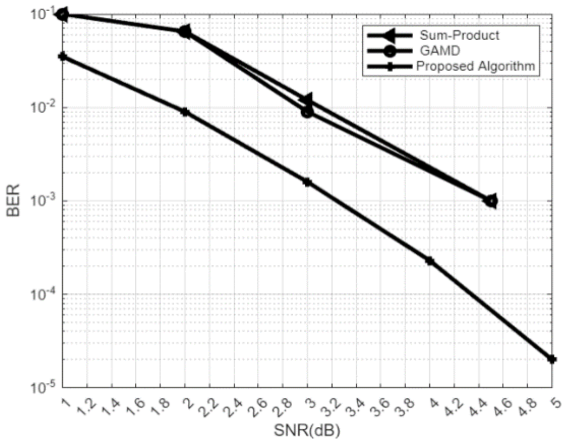

Figure 16. Performances of the proposed algorithm, GAMD and sum-product using LDPC (60,30)

5. CONCLUSION

In this article we have detailed our soft decoding algorithm according to the memetic algorithms using the dual code, we started by tuning the parameters used in our algorithm to obtain high performances and then we moved to simulations and compare it with different approaches, this decoder is simulated with several linear block codes over a AWGN channel, the results obtained show that it outperforms the competitors' algorithms and get a min BER corresponds to the min SNR choosing. The obtained results will encourage us in the future work to focus on implementing this decoder for the polar codes recently discovered.

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