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BER Performance and Decoding Time Enhancement of LTE Turbo Decoder

Yamaan I. Majeed [1], Ali F.Jumma [2]

Dr., Dept. of Electronics & Communication Engineering, Baghdad University, Baghdad, Iraq [1]

M.Sc. Student, Dept. of Electronics & Communication Engineering, Baghdad University, Baghdad, Iraq [2]

ABSTRACT: Turbo coding is one of the major blocks of LTE system**.**This paper provides a BER performance comparison of three different decoding algorithms for turbo decoder namely ***Maximum a Posteriori*** **(*MAP*) algorithm, Log-MAP algorithm, Max-Log-MAP algorithm.** And compare the BER performance of different turbo decoding iterations and measure the time taken for different number of decoding iterations.Finally test an early stopping mechanism depending on testing the cyclic redundancy check (CRC)attachment after every decoding iteration to reduce the decoding time.

KEYWORDS: MAP, Log-MAP, Max-Log-MAP, maximum number of iterations, CRC, time efficient decoder, BCJR algorithm

I. Introduction

The Long Term Evolution LTE represents a project within the 3GPP which is a collaboration agreement established in December 1998. 3GPP is a co-operation between ETSI (European Telecommunication Standards Institute), ARIB/TTC (Association of Radio Industries and business/ Telecommunication Technology Committee), CCSA (China Communication Standards Association), ATIS (Alliance for Telecommunication Industry Solutions) and TTA (Telecommunication Technology Association) [1]. The work on LTE has been started in release 7 of the 3GPP specifications which include the completion of its feasibility studies. Additional enhancements on High Speed Packet Access (HSPA) also have been included in this release. The Specification of LTE and SAE (System Architecture Evolution) represents as the main work done in release 8 of the 3GPP specifications [2].

The LTE is designed to provide higher data rates, improved power efficiency, low latency and better quality of service, therefore it is essential to evaluate and determine the possibilities and capabilities of this system in order to promote its utilizations smoothly and effectively. The Long Term Evolution Physical Layer (LTE PHY) carry both data and control information between a base station (eNodeB) and mobile user equipment (UE). The LTE PHY utilizes some advanced technologies like Orthogonal Frequency Division Multiplexing (OFDM), Multiple Input Multiple Output (MIMO), adaptive linking and turbo coding [3].

Turbo codes were proposed in [4]. Many factors led to the choice of turbo coding in LTE. The first is the near-Shannon-bound performance of turbo coders. Given a sufficient number of iterations in turbo decoding, turbo codes can have a BER performance far in exceeds of those of conventional convolutional coders. Furthermore, they lend themselves to adaptation, due to the use of an innovative rate-matching mechanism [5]

II. Related work

In [6] authors usedhighly punctured Turbo codes withrates up to 0.95 in channel coding to reach a throughput of 150 Mbps in 2X2 LTE MIMO system. Decoding such highly punctured code is a big challenge for decoder design in order to reach the desired throughput the authors used Log-MAP decoding algorithm to decode the encoded bits. In [7] authors proposed a flexibleand efficient VLSI architecture to solve the memory conflictproblem for highly parallel turbo decoders targeting multi-standard3G/4G wireless communication systems. To demonstratethe effectiveness of the proposed parallel interleaver architecture, they implemented an HSPA+/LTE/LTE-Advanced multi-standardturbo decoder with a 45nm CMOS technology. The implementedturbo decoder consists of 16 Radix-4 MAP decoder cores,

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andthe chip core area is 2.43mm2. When clocked at 600 MHz, thisturbo decoder can achieve a maximum decoding throughput of826 Mbps in the HSPA+ mode and 1.67 Gbps in the LTE/LTEAdvancedmode, exceeding the peak data rate requirements forboth standards.In [8] authors presented the first investigation of a combinedbit-width optimization of input data and internal data for an 8-state Turbodecoderbased on parameters relevant for UMTS. Simulation results forAWGN and Rayleigh-fading channels show that performance degradationcan be held below 0.11 dB using a 4-bit input data quantization.

III. THE LTE TURBO ENCODER

The structure of LTE turbo encoder is clarified in Figure 1. The turbo encoder composed of two constraint length 4 recursive systematic (i.e. one of the outputs is the input) convolutional (RSC) encoders concatenated in parallel.

The transfer function of the 8-state constituent code for the Parallel Constructed convolutional Code PCCC is:

$$G(D) = \left[1, \frac{g_1(D)}{g_0(D)}\right]$$

Where

$$g_0(D) = 1 + D^2 + D^3 g_1(D) = 1 + D + D^3$$

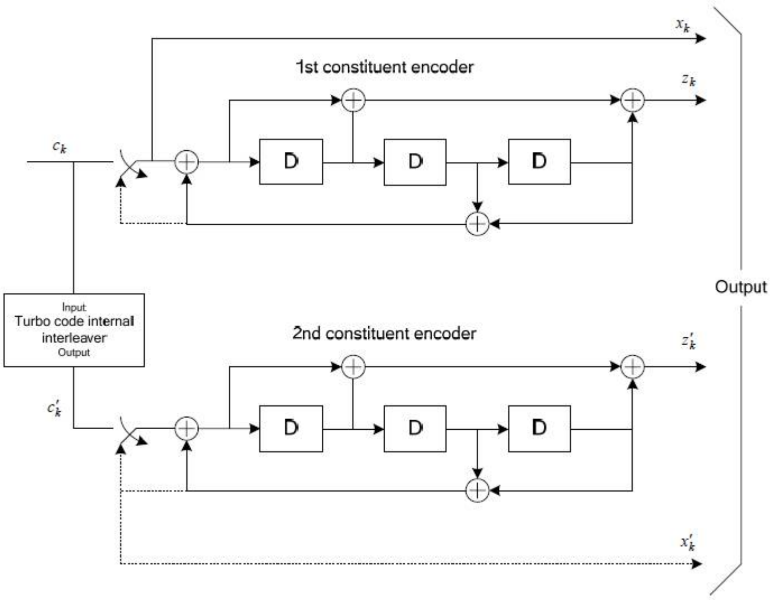

Figure 1. LTE turbo encoder

. The internal interleaver of turbo coding is based on Quadratic Permutation Polynomials (QPP) interleaver
The bits input to the turbo code internal interleaver are denoted by $c_0, c_1 \dots, c_{K-1}$, where K is the number of input bits. The bits output from the turbo code internal interleaver are denoted by $C'_0, C'_1, \dots C'_{K-1}$.

The relationship between the input and output bits is as follows:

$c'_i = c_{\pi(i)}, i = 0,1, \dots, (K-1)$

where the relationship between the output index *i* and the input index Π(i) satisfies the following quadratic form:

$$\Pi(\mathrm{i}) = (f_1 . i + f_2 . i^2) mod\ K$$

The parameters f_1 and f_2 depend on the block size K that defined in 3GGP standard[9]. The maximum and minimum code block size are specified so the block sizes are compatible with the block sizes supported by the turbo interleaver where minimum code block size = 40 bits and maximum code block size, Z = 6144 bits [9]. If the length of the input block, *B*, is more than the maximum code block size, the input block is segmented. When the input block is segmented, it is segmented into $C=[B/(Z-L)]$, where *L* is 24. Therefore, $C=[B/6120]$ code blocks.After segmentation, each code block has a 24-bit Cyclic Redundancy Check (CRC) attached to the end as shown in figure 2.

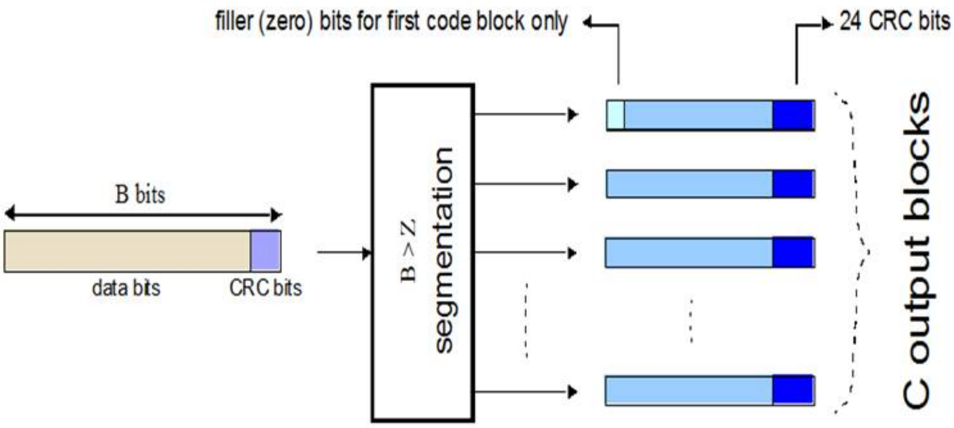

Figure 2. Code Block Segmentation and CRC Attachment

The generator polynomial for CRC attachment is defined by 3GPP [9] as:

$g_{CRC24B}(D) = [D^{24} + D^{23} + D^6 + D^5 + D + 1]$.

Applying L bits CRC attachment to a data block of arbitrary length, will detect a fraction $(1 - 2^{-L})$ of error bursts [10].

IV. LTE TURBO DECODER

The received sequence to the decoder and used by a decoding algorithm in order to find the original bit sequence u_k. The algorithm computes the a posteriori log-likelihood ratio $L(uk\backslash\mathbf{y})$, which it is a real number defined by the ratio

$$L(u_k/y) = \ln\frac{P(u_k = +1/y)}{P(u_k = +1/y)}$$

Where $L(u_k/y)$ is computed in this paper using three different algorithms:

1) *Maximum a Posteriori* (*MAP*) algorithm

In *Maximum a Posteriori* (*MAP*) algorithm$L(u_k/y)$ can be computed as

$$L(u_k/y) = \ln\frac{\sum_{R_1} P(s', s, y)}{\sum_{R_0} P(s', s, y)}$$

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$$= \ln \frac{\sum_{R_1} \propto_{k-1}(s')\gamma_k(s',s)B_K(s)}{\sum_{R_0} \propto_{k-1}(s')\gamma_k(s',s)B_K(s)}$$

Where $P(s',s,y)$ represents the joint probability of receiving sequence **y** and being in state s' at time k-1and in state s at the current time k, $R1$ means that the summation is computed over all the state transitions from s' to s that are related to message bits u_k= +1.in the other hand, the denominator $R0$ is the set of all branches originated by message bits uk = -1.as shown in figure 3 [11]. The variables α, γ and β are defined respectively as

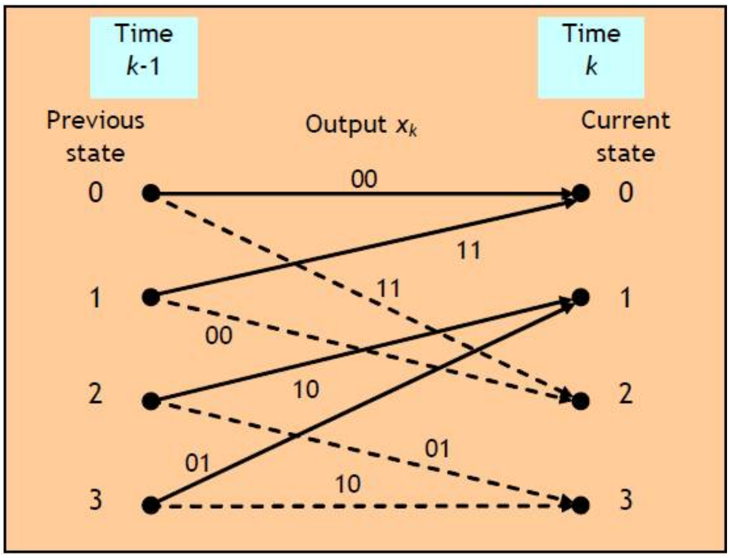

Figure 3: The convolutional code trellis diagram.

$$\gamma_k(s',s) = C_k e^{u_k L(u_k)/2} \exp\left(\frac{L_c}{2}\sum_{l=1}^{n} x_{kl}\, y_{kl}\right)$$

Where C_k is constant and L_C can be defined as

$$L_C = 4a\frac{E_C}{N_0} = 4aR_c\frac{E_b}{N_0}$$

Where No is the noise power spectral density, *a* is the *fading amplitude*, *Ec* and *Eb* are the transmitted energy per coded bit and message bit, respectively, and *Rc* is the code rate [11]

The other two parameters α and β are defined as

$$a_k(s) = \sum_{s'} \propto_{k-1}(s')\gamma_k(s',s)$$

Initial condition $a_0(s) = \begin{cases} 1 & s = 0 \\ 0 & s \neq 0 \end{cases}$

$$\beta_{k-1}(s') = \sum_{s} \beta_k(s)\gamma_k(s',s)$$

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Initial condition $\beta_N(s) = \begin{cases} 1 & s = 0 \\ 0 & s \neq 0 \end{cases}$

2) Log-MAP algorithm

In log-MAP algorithm L(uk |y) can be computed by the following eq.

$$L(u_k/y) = \underset{R1}{Max} * [A_{K-1}(s') + \Gamma_k(s', s) + B_k(s)] -$$

$$\underset{R0}{Max} * [A_{k-1}(s') + \Gamma_k(s', s) + B_k(s)]$$

Where

$$\Gamma_k(s', s) = \ln \gamma_k(s', s) = \ln C_k + \frac{u_k L(u_k)}{2} + \frac{L_c}{2} \sum_{l=1}^{n} x_{kl} y_{kl}$$

$$A_k(s) = \ln \alpha_k(s) = \max_{s'}* [A_{k-1}(s') + \Gamma_k(s', s)] A_0(S) \begin{cases} 0 & s = 0 \\ -\infty & s \neq 0 \end{cases}$$

$$B_{k-1}(s') = \ln \beta_{K-1}(S') = \max_{S}*[B_k(S) + \Gamma_k(s', s)] B_N(S) \begin{cases} 0 & s = 0 \\ -\infty & s \neq 0 \end{cases}$$

Where max*(a,b)=max(a,b)+$\ln(1 + e^{-|a-b|})$ [9].

3) Max-Log-MAP algorithm

The max log MAP algorithm uses the same equations of log MAP algorithm except that the max*(a, b) is computed as

max*(a ,b) = max(a ,b).

The turbo decoder is based on using two A Posteriori Probability (APP) decoders with two interleavers in an iterative loop. The same trellis structure used in the turbo encoder is used in the turbo decoder, using the same interleaver. There is one different that the turbo decoder use an iterative operation. The computational complexity and performance of the turbo decoder is directly relate to the number of iterations [11].
The turbo decoder shown in figure 4 uses two decoders applying one of the last three mentioned algorithms to iterative decoding where

$$L(u_k/y) = L(u_k) + L_C y_{kl} + L_e(u_k)$$

Where after a specified number of iterations the output sequence can be found as:

$$\hat{u}_k = sign[L(u_k/y)] = sign\{P^{-1}[L_2(u_k/y)]\}$$

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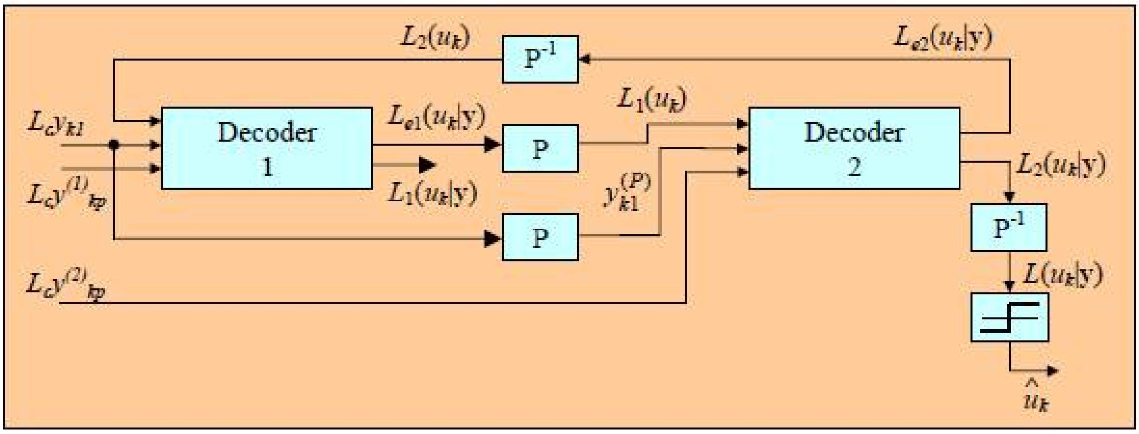

Figure 4. Turbo decoder

V. SIMULATED SYSTEM BLOCK DIAGRAM

The system block diagram shown in figure 5 was simulated using MATLAB 2015a

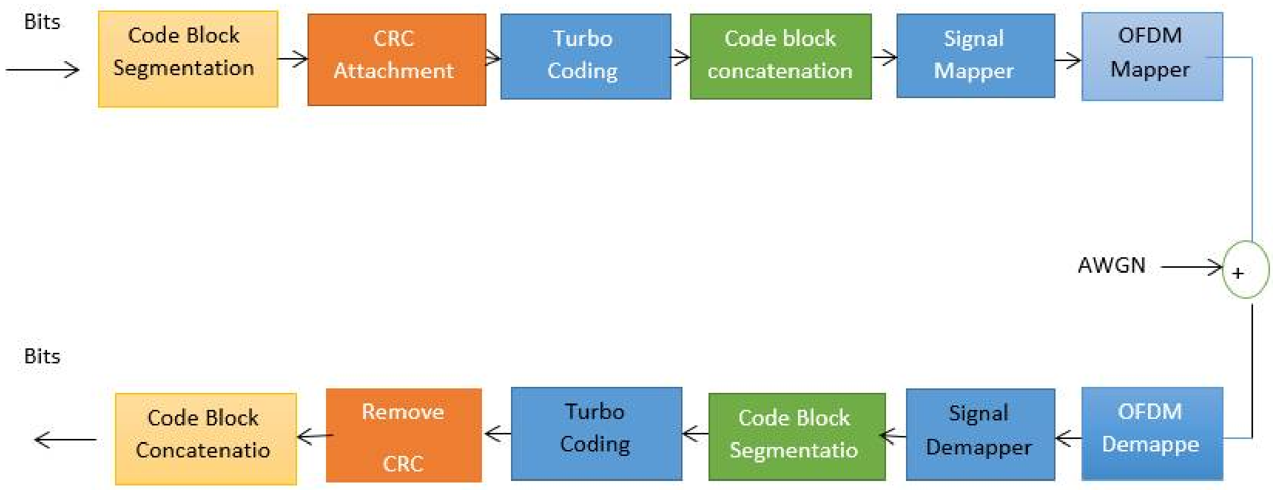

Figure 5. Simulated block diagram

The code block segmentation and CRC attachment splits the code stream into smaller code blocks if the code stream is longer than the maximum code bock size allowed by the turbo interleaver then it adds 24 CRC bits at the end of code. Turbo encoder encodes the segmented sequence with code rate 1/3. The code block concatenation is sequentially concatenating the outputs from the turbo encoder. The signal mapper modulates the sequence using QPSK modulation. The OFDM mapper splits the spectrum into narrower parallel channels named as subcarriers and the information is transmitted on these parallel channels at a reduced rate. The channel is simulated as AWGN channel. At the receiver end, the receiver will perform the inverse operations of the transmitter operations. The turbo decoder will decodes the received sequence using three different algorithms that mentioned previously with different number of iterations that specified before starting simulation [12].

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VI. RESULTS

As mentioned previously, three different decoding algorithms were used in this thesis (MAP, Log-MAP, and Max-Log-MAP). The performance of these three algorithms is shown in Figure 5. As we see from figure 5 the BER of Max-Log-MAP is higher than the other two algorithms, which they approximately have the same BER performance.MAP algorithm has an important disadvantage that it needs to perform many multiplications while log-MAP algorithm uses the same formulas of MAP algorithm with less number of multiplications. So its performance equals the performance of the MAP algorithm although it is simpler, which for that season it is preferred in implementations. The Max-Log-MAP algorithm uses approximations to simplify the decoding procedure and reduce the number of multiplications, therefore its performance is worse.

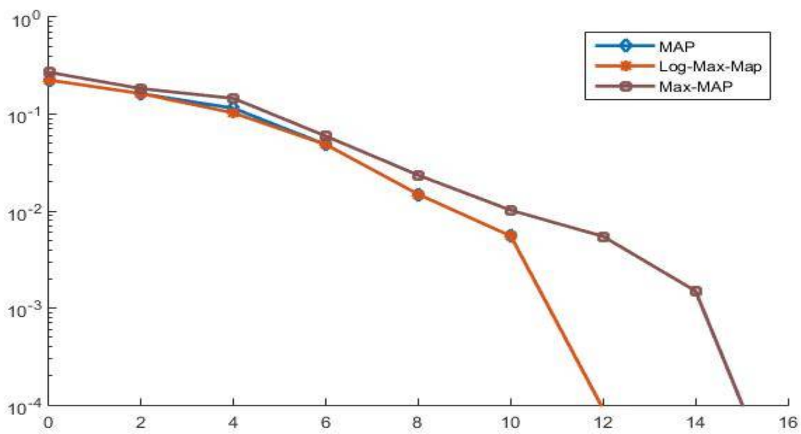

Figure 6: BER performance of turbo decoding algorithms

The performance of different number of turbo decoding iterations is shown in Figure 6. We can see from figure 6 that as we increase the iterations number from one to six the shape of the BER curve enhancing dramatically by increasing the number of iteration. The performance of turbo encoder depends on the number of iterations performed in the turbo decoder. That means, for a given turbo coder the BER performance becomes much better with a greater number of decoding iterations.

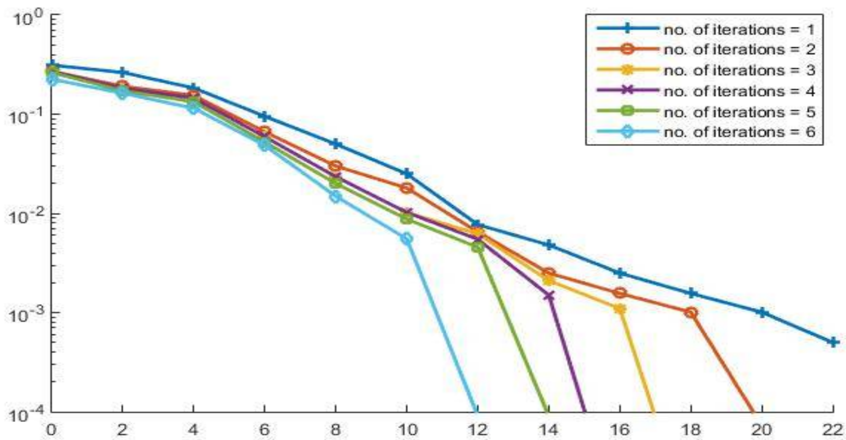

Figure 7: BER performance of different turbo decoding iterations

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In the tending to implement an efficient turbo decoder one can face clear tradeoff. On one hand, the performance and accuracy of the turbo decoder is relates to the number of iterations performed. Increasing the number of iterations means more accurate results. On the other hand, the time taken and the computational complexity of the turbo decoder is directly proportional to its number of iterations. Table 1 shows measurement of the transceiver computation time as a function of number of iterations where the time measurement was done using HP Pavilion g6 Notebook PC ,windows 8, Processor Intel® Core™ i7- 2.10 GHz CPU with RAM 6 GB.

Table 1*Transceiver computation time as a function of number of iterations*

no. of iterations	Transceiver time computation (sec)
1	1173.68
2	1902.8
3	2655.48
4	3118.59
5	3866.59
6	4467.43

By calling the fact that for a given received bit sequence the turbo decoder may exceed the maximum number of iterations without correcting all errored bits and for other received bit sequence the turbo decoder may correct all the errored bits before the maximum number of iteration executed. We can check the errors in every iteration and if on error detected. We stop the decoding process even that the maximum number of iterations has not been executed.In this paper by checking the CRC - that attached in the transmitter by LTE stander mainly to help in detecting errors and measure the throughput in the receiver- to detect the presence or absence of any bit errors at the end of every iteration. When the CRC check indicates that there is no errors, the process of iterative decoding will forcibly ended. The flowchart in figure 7 explains the procedure of early stopping turbo decoding mechanism.

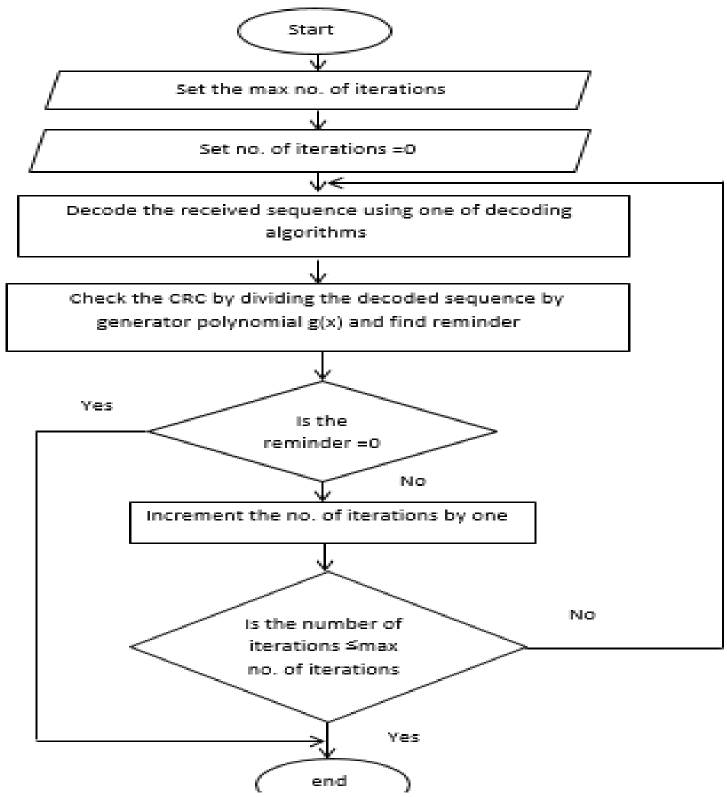

Figure 8: Flowchart of early stopping mechanism using CRC checking

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With maximum number of iterations equal to six without CRC check. The time taken by the function to end turbo decoding was 4467.4255 seconds. While with the same maximum number of iterations and with CRC checking. The time taken by the function to end turbo decoding was 3514.7544 seconds with the same BER performance.
From time measurement we can see a great time enhancement by using the early stopping mechanism coming from the fact that for many received sequences the turbo decoder will correct all the errors before achieving the maximum number of iterations and finding a mechanism to stop the decoding process when no errors detected will save time without affecting on the BER performance.

VII. CONCLUSION

From the results we can conclude the following

1- MAP and Log-MAP algorithms have the same performance since log-MAP algorithm uses exact formulas of MAP algorithm with less number of multiplications and their BER performance is better than Max-Log-MAP algorithm.
2- For a given turbo encoder the BER performance becomes successively better with a greater number of decoding iterations.
3- The time taken and the computational complexity of the turbo decoder increasing proportional to its number of iterations.
4- For many received sequences the turbo decoder will correct all the errors before achieving the maximum number of iterations. So using early stopping mechanism by checking the CRC at the end of every decoding iteration will reduce the decoding time without affecting on the BER performance.

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