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Jacobian approximation of the Sum-Alpha stopping criterion

Aissa Ouardi
Laboratory Technology of Communication, Faculty of Technology, Department of Electronics, University of Saida Dr. Moulay Tahar, Saida, Algeria

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ABSTRACT

This article will report the development of new application of the Sum-Alpha stopping criterion to the case of log – maximum a posterioru Log-MAP turbo decoding. It shows how to adapt Sum-Alphas quantities when using the Log-MAP algorithm and how to deduce a good decision threshold. We apply a logarithm to the quantity Sum-Alpha which is evaluated by the same Jacobian logarithm of the Log-MAP algorithm. We call this new adaptation Jacobian Approximation of Sum-Alpha (JASA) criterion. The simulation results demonstrate that the JASA criterion achieves comparable performance (in terms of bit error rate (BER) and frame error rate (FER)) to the Sum-Alpha and cross-entropy (CE) criteria, with the same average number of iterations.

Corresponding Author:

Aissa Ouardi
Laboratory Technology of Communication, Department of Electronics
University of Saida Dr. Moulay Tahar
Saida, Algeria
Email: aissa.ouardi@univ-saida.dz

1. INTRODUCTION

Study in [1], the new Sum-Alpha stopping criterion is proposed for turbo decoding [2]. It was initially proposed for turbo decoders that use the MAP algorithm [3]. It shows that we can have information about the decoding quality of the frame and make a decision to stop turbo decoding. Sum-Alpha uses only the alpha values ($\alpha_m(k)$) calculated in the forward direction of the MAP algorithm (m is the m^{th} state of the encoder trellis and k is the time). It calculates the sum of the competitors by discarding the maximum value $\alpha_{max}(k)$ of $\alpha_m(k)$ at the time k. This criterion is special because it does not wait for the end of the calculations of all log-likelihood ratios (LLR) [1]. Moreover, it uses practically no memory storage. However, In practical implementations, the log-based algorithms are preferred. The application of this criterion to Log-MAP turbo decoding [4] requires some adaptations because the computation in the logarithmic domain changes the range of variation of the alphas and the way of evaluating this criterion. In addition, the decision threshold of the criterion must also be adapted. This adaptation is necessary because the Log-MAP algorithm is the most attractive algorithm given its low complexity and its performance. Its loss regarding to the optimal MAP algorithm is negligible [4]. Recently [5], a first adaptation of the Sum-Alpha criterion is proposed for Log-MAP turbo decoding. This criterion called Sum-Log consists of summing the quantities Log alpha $A_m(k)$ calculated in the logarithmic domain by the Log-MAP algorithm. Then, it compares this sum with an appropriate threshold and makes a decision about the end of decoding. This criterion is presented in section 7. In this article, we present a new adaptation and we show how to transfer the Sum-Alpha criterion to the logarithmic domain and how to derive a suitable decision threshold. We also compare its performances with the cross-entropy (CE) and Sum-Alpha criteria [6], [7]. We call this new adaptation Jacobian Approximation of Sum-Alpha (JASA) criterion, because it represents a logarithm of sum alpha quantities. However, in [5], a sum of logarithmic quantities is used (Sum-Log). In sections 5 to 7, the criteria CE, Sum-α and Sum-Log are briefly presented. The reader finds other criteria in other references. Part 4, gives a state of the art of these turbo stopping techniques.

2. TURBO ENCODER, TURBO DECODER AND SYSTEM MODEL

The turbo encoder consists of two identical parallel recursive systematic convolutional (RSC) encoders. The information bit frame {$u(k)$} is encoded by the encoder RSC1, then interleaved and processed by RSC2. Each information bit produces an information bit u(k) with two redundant bits $c_1(k)$ and $c_2(k)$ (Figure 1). *I* in Figure 1 represents the interleaver.

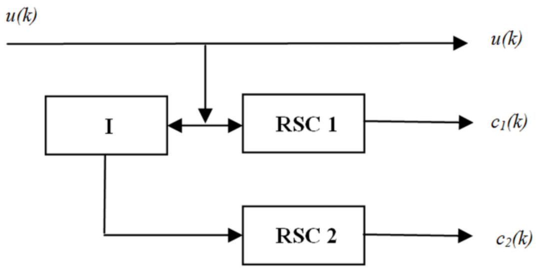

Figure 1. Turbo encoder

After binary phase shift keying (BPSK) mapping, the symbols {$x_u(k)$, $x_1(k)$, $x_2(k)$} are obtained. These symbols are transmitted over an additive white Gaussian noise channel. The received samples are {$y_u(k)$, $y_1(k)$, $y_2(k)$}. The received frame is passed to the turbo decoder of the Figure 2. D represents the deinterleaver.

The turbo decoder consists of two soft input soft output (SISO) decoders. The first uses the a priori information *La* from the previous iteration, the noisy observations of both the information bit and the first redundancy bit. At iteration *i*, the first decoder provides the Log-Likelihood Ratio LLR $L_1^{(i)}(u(k))$ of the systematic bit $u(k)$ which contains the extrinsic information $Le_1^{(i)}(u(k))$ (decoder contribution). This information is obtained after subtracting the a priori quantity $La_1^{(i)}(u(k))$ and the channel observation $(2/\sigma^2)$ $y(k)$ (σ^2 is the noise variance). After interleaving, extrinsic information $Le_1^{(i)}(u(k))$ becomes a priori information $La_2^{(i)}(u(k))$ which is ready to be used by the second SISO decoder (Figure 2). After *calculating* the LLR, the extrinsic information is obtained by (1):

$$Le_1^{(i)}(u(k)) = L_1^{(i)}(u(k)) - La_1^{(i)}(u(k)) - L_c y_u(k) \tag{1}$$

L_c is the channel reliability;

$$L_c = \frac{2}{\sigma^2} \tag{2}$$

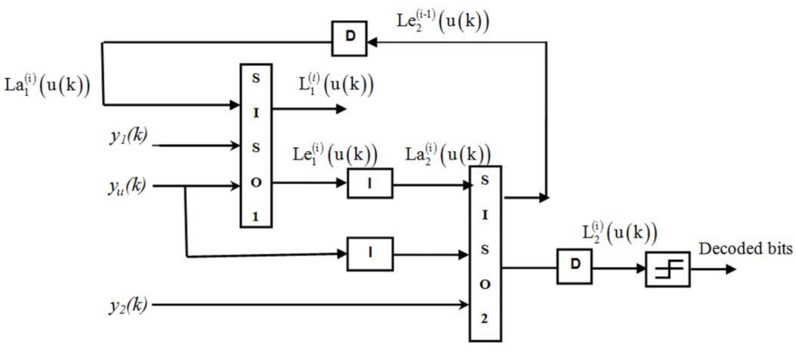

Figure 2. Turbo decoder

3. LOG-MAP ALGORITHM

The Log-MAP algorithm [4] is a simplified version of the well-known maximum a posteriori MAP algorithm. Log-MAP calculates the logarithms of the gamma, alpha and beta quantities of the MAP algorithm.

$$\Gamma_{m'm}(k) = log\left(\gamma_{m'm}(k)\right) \tag{3}$$

$$A_m(k) = log\left(\alpha_m(k)\right) \tag{4}$$

and

$$B_m(k) = log\left(\beta_m(k)\right) \tag{5}$$

Knowing that,

$$\alpha_m(k) = \sum_{m'=1}^{M_{tr}} \alpha_{m'}(k)\gamma_{m',m}(k) \tag{6}$$

$$\beta_m(k) = \sum_{m'=1}^{M_{tr}} \beta_{m'}(k+1)\gamma_{m',m}(k+1) \tag{7}$$

The transition between states *m'* and *m* in the encoder's trellis is represented by (*m'*, *m*). In this case, the quantity $A_m(k)$ is calculated by (8):

$$A_m(k) = log\left(\sum_{m'=1}^{M_{tr}} \alpha_{m'}(k-1)\gamma_{m'm}(k)\right) = log\left(\sum_{m'=1}^{M_{tr}} e^{A_{m'}(k-1)} e^{\Gamma_{m'm}(k)}\right) \tag{8}$$

Using the notion of "Jacobian Logarithm" [4] which is described by (9):

$$log(e^{z_1} + e^{z_2}) = max(z_1, z_2) + log\left(1 + e^{-|z_2 - z_1|}\right) = max^*(z_1, z_2) \tag{9}$$

Log-alpha quantities can be approximated by (10):

$$A_m(k) = log\left(\sum_{m'=1}^{M_{tr}} e^{A_{m'}(k-1)+\Gamma_{m'm}(k)}\right) = \max_{m'=1,\dots,M_{tr}}{}^{*}\left(A_{m'}(k-1)+\Gamma_{m'm}(k)\right) \tag{10}$$

Log-beta can be calculated by (11):

$$B_{m'}(k) = \max_{m'=1,\dots,M_{tr}}{}^{*}\left(B_m(k+1) + \Gamma_{m'm}(k+1)\right) \tag{11}$$

The Log Likelihood Ratio can be evaluated by [4]:

$$L\left(u(k)\right) = \overset{*}{\underset{}{max}}^{m',m/u(k)=1}\left[A_{m'}(k-1) + \gamma_{m',m}(k) + B_m(k)\right] - \overset{*}{max}^{m',\frac{m}{u(k)}=0}\left[A_{m'}(k-1) + \gamma_{m',m}(k) + B_m(k)\right] \tag{12}$$

Because for the MAP algorithm:

$$L\left(u(k)\right) = log\left(\frac{\sum_{m',m/u(k)=1} \alpha_{m'}(k-1)\gamma_{m',m}(k)\beta_m(k)}{\sum_{m',m/u(k)=0} \alpha_{m'}(k-1)\gamma_{m',m}(k)\beta_m(k)}\right) \tag{13}$$

Finally, we can make a decision on the decoded bits:

$$L\left(u(k)\right) \underset{\hat{u}(k)=0}{\overset{\hat{u}(k)=1}{\gtrless}} 0 \tag{14}$$

4. STATE OF THE ART OF TURBO STOPPING CRITERIA

Researchers have contributed by proposing several stopping techniques for turbo decoding. Recently, two stopping techniques are proposed for MAP and Log-MAP turbo decoding. The first called Sum-Alpha [1] calculates the sum of the alpha probabilities of the MAP algorithm. The second called Sum-Log [5] is more attractive because it is proposed for the Log-MAP algorithm.

Apart from these two techniques which use alphas and log alphas, most of the others are based on LLRs. the CE is proposed in [6] to stop the turbo decoding. Research by AlMahamdy and Dill [8] exploits the identification of undecodable frames. Another criterion [9] proposes to exploit extrinsic information and LLRs for LTE turbo codes. [10] shows that mutual information between extrinsic information can be used to design an efficient stopping criterion. [11] proposes the minsumP stopping criterion which matches the rule based on the minimum absolute value of LLRs. [12], [13] to SISO-APP Benedetto's decoding algorithm [14]. Research by Wu *et al.* [15] proposes a novel iteration stopping criterion derived from an approximation of the mutual information between encoded bits and soft decoder outputs. The criterion proposed in [16] calculates the average of inverse absolute LLR values and compares it against a fixed threshold to determine iteration termination. The technique proposed in [17] uses the notion of average entropy and stops turbo decoding when there is not a, or little, reduction of this quantity.

Other methods manipulate also LLRs to stop turbo decoding. We can use their mean [18], their variance [19], or their sum [20] to stop turbo decoding. Reader is invited to consult the references [21]-[25].

5. CROSS-ENTROPY RULE

The cross-entropy rule CE [6] uses, at each iteration, the LLRs evaluated by the second decoder of successive iterations *i* and *i*-1. Let $L_1^{(i)}(u(k))$ be the LLR of bit u(k) at the output of the first decoder. $Le_2^{(i-1)}(u(k))$ and $Le_2^{(i)}(u(k))$ are respectively its extrinsic information at the output of the decoder soft input soft output SISO2 of the iterations *i*-1 and *i*.

The rule calculates the difference between extrinsic information from consecutive iterations *i*-1 and *i*, $\Delta Le_2^{(i)}(u(k))$ by (15):

$$\Delta Le_2^{(i)}\big(u(k)\big) = Le_2^{(i)}\big(u(k)\big) - Le_2^{(i-1)}\big(u(k)\big) \tag{15}$$

The same quantity can be evaluated using the LLRs calculated by the two decoders of the iteration *i*

$$\Delta Le_2^{(i)}\big(u(k)\big) = L_2^{(i)}\big(u(k)\big) - L_1^{(i)}\big(u(k)\big) \tag{16}$$

For iteration *i*, the cross-entropy is defined by (17):

$$CE(i) = \sum_{k=1}^{N} \frac{\left|\Delta Le_2^{(i)}(u(k))\right|^2}{e^{\left|L_1^{(i)}(u(k))\right|}} \tag{17}$$

The frame can be considered correct if:

$$CE(i) < \varepsilon \tag{18}$$

The threshold ε of the CE criterion must be chosen in the interval [6]

$$10^{-2}CE(1) \leq \varepsilon \leq 10^{-4}CE(1) \tag{19}$$

6. SUM-ALPHA CRITERION

The Sum-α criterion [1] gives early information about the decoding quality (frame decoded correctly or not) even before calculating the LLRs and before making a decision on the information bits. It calculates, at each instant *k*, the sum of the alphas $\alpha_m(k)$ (of the MAP algorithm) by discarding the maximum value $\alpha_{max}(k)$ and then evaluating a cumulative sum of these quantities until the end of the frame. This cumulative sum is normalized by the length of the information frame *N*. The result is then compared with a threshold *T*. If the result is less than *T*, the frame can be considered correct and turbo decoding can be stopped.

Therefore, the Sum-α criterion consists of [1]:

a. After calculating the alphas $\alpha_m(k)$ ($m=1, ..., M_{tr}$) at time *k*, calculate the quantity $Sum_c(k)$ by (20):

$$Sum_c(k) = \left(\sum_{m=1}^{M_{tr}} \alpha_m(k)\right) - \alpha(k)_{max} \tag{20}$$

Note that this quantity can be evaluated simply by (21):

$$Sum_c(k) = 1 - \alpha(k)_{max} \tag{21}$$

Because

$$\sum_{m=1}^{M_{tr}} \alpha_m(k) = 1 \tag{22}$$

b. Calculate the sum of the $Sum_c(k)$ of all moments ($k=1, ..., N$).

$$Sum\alpha = \frac{\sum_{k=1}^{N} Sum_c(k)}{N} \tag{23}$$

c. If '$Sum\alpha$' is less than a threshold 'T', then we can stop the turbo decoder.

The Sum-α stopping rule for turbocodes is an early technique with reduced complexity and without memory storage [1]. However, in the logarithmic domain, it requires some modifications. In practice, the Log-MAP algorithm replaces the MAP algorithm due to its simplicity and low complexity. Thereafter, the recent Sum-Log stopping criterion is detailed. In section 8, we present our new adaptation of the Sum-Alpha criterion to Log-MAP turbo decoding. We call this technique the JASA criterion.

7. SUM-LOG CRITERION

Sum-Log stopping criterion [5] is presented in two versions. The first approach utilizes the quantities $A_m(k)$ (where $A_m(k)=log(\alpha_m(k))$) computed by the Log-MAP algorithm. A summation is then applied following the rejection of the maximum value $A_{max}(k)$. The following steps describe the progress of the first criterion Sum-Log-1:

When performing Log-MAP algorithm,

a. At time k, calculate $A_m(k)$ then determine

$$A_{max}(k) = max\left(A_m(k)\right) \tag{24}$$

b. Compute the sum of all $A_m(k)$ values while excluding $A_{max}(k)$

$$SumL(k) = \left(\sum_{m=1}^{M_{tr}} A_m(k)\right) - A(k)_{max} \tag{25}$$

c. Calculate the quantity $SumLA$.

$$SumLA = \frac{\sum_{k=1}^{N} SumL(k)}{M_{tr}^2\ N} \tag{26}$$

N denotes the frame length and M_{tr} represents the number of trellis states

d. If $SumLA<Th1$, then decoding is stopped and the frame is verified as correct.

The threshold Th_1, determined through simulation, depends on the interleaver size N [5]. For decoded frames, $A_{max}(k)$ will tend to 0. It may be kept without discarding it in (25). This second criterion is called Sum-Log-2 [5]. The second step becomes;

$$SumL(k) = \left(\sum_{m=1}^{M_{tr}} A_m(k)\right) \tag{27}$$

The other steps do not change.

8. JACOBIAN APPROXIMATION OF THE SUM-ALPHA STOPPING RULE FOR LOG-MAP TURBO DECODING: THE PROPOSED JASA CRITERION

Let's resume the evaluation of the Sum-α criterion:

$$Sum\alpha = \frac{\sum_{k=1}^{N} Sum_c(k)}{N} = \frac{\sum_{k=1}^{N}((\sum_m \alpha_m(k)) \ - \alpha_{max}(k)}{N} \tag{28}$$

This equation can be written in the following form:

$$Sum\alpha = \frac{\sum_{k=1}^{N} Sum_c(k)}{N} = \frac{\sum_{k=1}^{N}((\sum_m \alpha_m(k))}{N}, \alpha_m(k) \neq \alpha_{max}(k) \tag{29}$$

Since we are interested in the use of the Log-MAP algorithm, we are obliged to use the log alpha quantities $A_m(k)$. Using (4) and (29), we have,

$$Sum\alpha = \frac{\sum_{k=1}^{N}(\sum_m e^{A_m(k)})}{N}, A_m(k) \neq log(\alpha_{max}(k)) \tag{30}$$

By introducing the logarithm, we obtain:

$$log(Sum\alpha) = log\left(\frac{\sum_{k=1}^{N}(\sum_m e^{A_m(k)})}{N}\right) = log\left(\sum_{k=1}^{N}\left(\sum_m e^{A_m(k)}\right)\right) - log(N), \quad A_m(k) \neq A_{max}(k) \tag{31}$$

Which can be calculated by the jacobian approximation [4]:

$$log(Sum\alpha) = \left(\underset{\substack{k=1,\dots,N \\ A_m(k)\neq A(k)_{max}}}{max^*}\left(A_m(k)\right)\right) - log(N) \tag{32}$$

Where the *max** function is defined by [4],

$$max^*(z_1, z_2) = max(z_1, z_2) + log\left(1 + e^{-|z_2 - z_1|}\right) = log(e^{z_1} + e^{z_2}) \tag{33}$$

The *max** function of multiple variables may be calculated by [4].

$$max^*(z_1, z_2, \dots\dots, z_P) = max^*\left(z_P, (z_{P-1}, \dots\dots, max^*\left(z_3, max^*(z_1, z_2)\right)\right) \tag{34}$$

By applying the comparison with the threshold to make a decision, the frame will be decided correct if:

$$log(Suma) < log(T) \tag{35}$$

Let *LS* be the quantity (in (32)).

$$LS = \left(\underset{\substack{k=1,\dots,N \\ A_m(k)\neq A(k)_{max}}}{max^*}\left(A_m(k)\right)\right) \tag{36}$$

Finally, using this new stopping criterion JASA, the frame will be decided correct if:

$$LS < log(T) + log(N) \tag{37}$$

The new threshold of the JASA criterion is therefore:

$$T' = log(T) + log(N) \tag{38}$$

9. RELATION BETWEEN THE GOOD THRESHOLD OF THE JASA CRITERION AND THAT OF THE SUM-ALPHA CRITERION

Given the size of the interleaver *N*, we will try to find a good threshold. The first step consists in determining the range of variation of the threshold in the logarithmic domain or else a minimum threshold from which the complexity reaches the maximum number of iterations. The next step is to find a good threshold by increasing the value of threshold that caused the maximum number of iterations.

For example, for a frame of length N=5120, the threshold T=0.001 is acceptable for the Sum-α criterion [1]. The new threshold of the JASA criterion applied to the Log-MAP turbo decoding becomes:

$$T' = ln(T) + ln(N) = 1.633 \quad (39)$$

This threshold, in the logarithmic domain, gave the same performances of the turbo decoder with complete complexity (here, Average number of iterations=10 (Full)). So, it didn't stop turbo decoding (although T=0.001 worked well for Sum-α [1]).

Figure 3 gives a simple method to determine a good threshold for the new JASA criterion. We start by using the threshold of the Sum-α criterion and we determine the new threshold of the JASA criterion adapted to the Log-MAP turbo decoding by using (37). If this threshold gives the maximum average number of iterations, we try to increase it until a good threshold is obtained. The beginning threshold T (of the Sum-α criterion) is therefore only used to locate the start of the search interval. This mechanism is summarized in the schema of Figure 3.

Now, let us start from the threshold which gives the maximum number of iterations (here T'=1.633), and let us start to increment T' until we obtain a minimum threshold T'_{min} which gives a low average number of iterations. The usable threshold T'_u must be greater than T'_{min}. That's to say:

$$T'_u > T'_{min} \quad (40)$$

But, it must not be very large because it will degrade the BER and the FER by reducing the average number of iterations.

For an interleaver of size 5120, the simulations have shown that T'_{min}=2.71 (for signal-to-noise ratio (SNR) SNR=0.5 dB, average number of iterations=9.23<10). We chose a threshold T'_u=3. In the linear domain, T'_u=3 corresponds to T=4 10^{-3} because:

$$T'_u = ln(T) + ln(N) \approx 3 \quad (41)$$

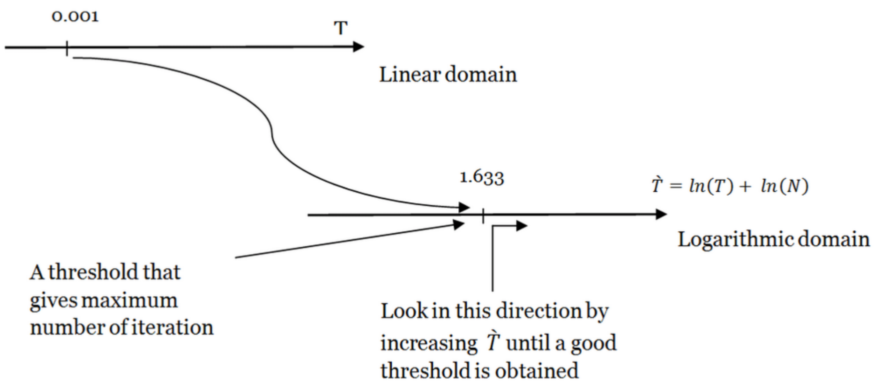

Figure 3. Mechanism to find a good threshold for the new stopping criterion JASA

10. RESULTS AND DISCUSSION

The simulations are carried out under the following conditions:

- Convolutional turbocode built from a recursive systematic convolutional RSC encoder with generator polynomials of $[1, 35/23]_{oct}$ without puncturing.
- BPSK modulation.
- Gaussian channel.
- Frames before encoding: 5120 bits.
- Transmission of 5000 frames.
- Maximum number of iterations: 10.
- Size of interleaver: 5120.
- Interleaver: Pseudo-random S-random interleaver.

So as not to clutter the figures of the curves, a comparison has been presented with the CE and Sum-Alpha criteria. The results presented in [5] show that the other criterion (Sum-Log) gives the same performance. For the JASA criterion, the threshold used is $T'_u = 3$. The simulation results showed that the

JASA rule demonstrated equivalent performance to the CE and Sum-Alpha criteria. The JASA criterion gave the same BER (Figure 4) and the same FER (Figure 5) of the two criteria. However, it is vulnerable to the choice of the threshold T'_u in the logarithmic domain. This threshold must be well chosen because it can cause performance degradation if it is too large, or it can waste computational complexity by using the total number of iterations (10 in this example) if it is too small.

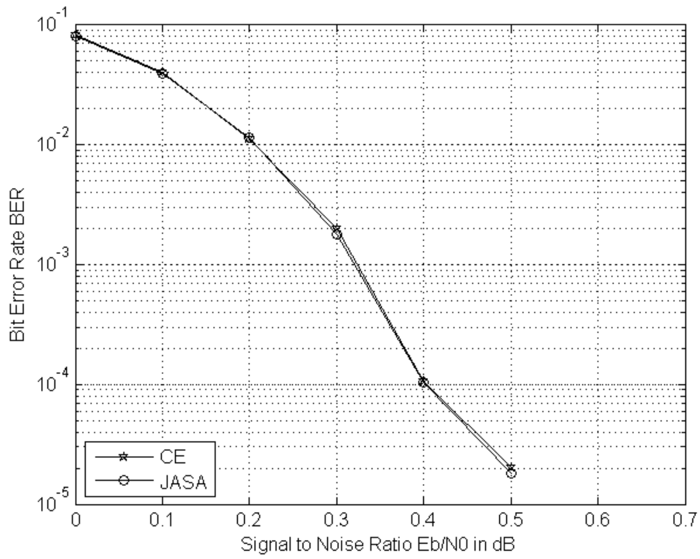

Figure 4. BER performance of the Log-MAP turbo decoder using the JASA stopping rule, compared with the CE technique

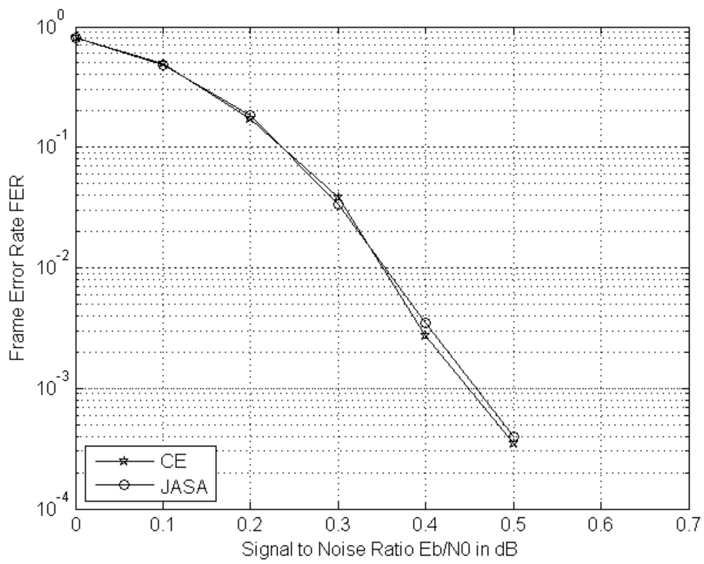

Figure 5. FER performance of the Log-MAP turbo decoder using the JASA stopping rule.

Regarding the stopping of turbo decoding, Figure 6 demonstrates that the JASA rule requires nearly identical average number of iterations compared to the CE and Sum-Alpha criteria. At the SNR of 0.6 dB, the three criteria consume on average nearly 5 iterations. Finally, note that these criteria are applied at the second 2^{nd} decoder. The application of the stopping criteria to the two decoders 1 and 2 does not change the behaviour of their performances.

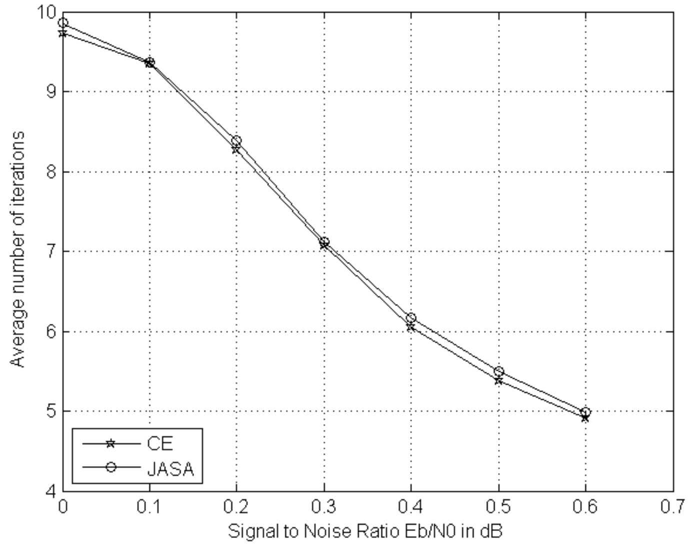

Figure 6. Average number of iteration of the Log-MAP turbo decoder using the JASA stopping rule.

11. CONCLUSION

This paper presents a novel adaptation of the Sum-Alpha rule to Log-MAP turbo decoding using the Jacobian approximation which is low complexity. We called this new adaptation Jacobian Approximation of Sum-Alpha JASA criterion. This criterion (JASA) applies the same stopping principle of the Sum-Alpha criterion by manipulating the Log alpha quantities and by redefining the decision threshold in the logarithmic domain. The simulation results showed the good functioning of the JASA criterion while guaranteeing the same complexity of the CE and Sum-Alpha criteria. The most important point is the choice of decision threshold which strongly depends on the size of the interleaver.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Aissa Ouardi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

CONFLICT OF INTEREST STATEMENT

Author states no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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BIOGRAPHY OF AUTHOR

Aissa Ouardi received the B.Eng. from the Telecommunications Institute, Oran, Algeria, in 2000, M.Sc. in Signal processing, from Polytechnic Military School, Algiers, Algeria in 2003 and Ph.D. from University of Sidi Belabes, Algeria, in 2012. He is an Associate Professor at the faculty of Technology, at Dr. Moulay Tahar University of Saida, Algeria. He is a membership of the Laboratory of Technology of Communications (LTC). His research interests are in Turbocommunications and coding. He can be contacted at email: aissa.ouardi@univ-saida.dz.