Paper

An Efficient Early Iteration Termination for Turbo Decoder

P. Salija and B. Yamuna

Department of Electronics and Communication Engineering, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India

Abstract—Turbo code finds wide applications in mobile communication, deep space communication, satellite communication and short-range communication despite its high computational complexity and iterative nature. Realizing capacity approaching turbo code is a great achievement in the field of communication systems due to its efficient error correction capability. The high computational complexity associated with the iterative process of decoding turbo code consumes large power, introducing decoding delay, and reducing the throughput. Hence, efficient iteration control techniques are required to make the turbo code more power efficient. In this paper, a simple and efficient early iteration termination technique is introduced based on absolute value of the mean of extrinsic information at the component decoders of turbo code. The simulation results presented clearly show that the proposed method is capable of reducing the average number of iterations while maintaining performance close to that of fixed iteration termination. The significant reduction in iteration achieved by the method reduces decoding delay and complexity while maintaining Bit Error Rate performance close to standard fixed iteration turbo decoder.

Keywords—early termination, complexity reduction, mean of extrinsic information, turbo decoder.

1. Introduction

One of the major challenges in wireless communication is to establish energy efficient and performance optimized error correction over dynamic channel conditions and to prolong the network/hardware lifetime. The near Shannon's performance and excellent Bit Error Rate (BER) performance of turbo code has resulted in its wide use in the entire range of wireless communication regardless of its high computational complexity [1], [2]. Key to the outstanding performance of turbo code is the parallel concatenation, interleaved recursive systematic operation, and iterative exchange of extrinsic information [3], [4]. Turbo decoding being an iterative process, its decoding delay, computational effort and energy consumption increase linearly with iterations [5]. The number of iterations required to obtain an acceptable performance depends on the channel characteristics [6]. The fact that sometimes an acceptable performance is not achieved even with infinite number of iterations has motivated researchers to find low complexity performance optimized turbo decoding techniques.

The objective of the early termination is to reduce unnecessary computation complexity, power consumption and decoding delay. If the channel conditions are bad, performance improvement is negligible even after infinite iterations whereas under good channel conditions desired performance may be reached after just a few iterations. Therefore, finding the appropriate condition to terminate the turbo decoding iteration while maintaining a tradeoff between acceptable performance and complexity is a major challenge [7]. Early iteration termination techniques based on soft and hard information have been reported. Sign Change Ratio (SCR) [8], an early termination technique compares the sign differences between two consecutive iterations. Mean Estimate (ME) [9] technique is based on mean of the absolute values of Log Likelihood Ratios (LLRs). In Mean Reliability [10], [11] based stopping technique, the iteration is stopped when the means of the absolute value of extrinsic information at two consecutive iterations are same. Hard Decision Aided (HDA) [8] stopping technique based on the hard values at the output of component decoder, stops iteration when the hard decision at two consecutive iterations is the same. Sign Difference Ratio (SDR) [12], [13], uses the number of sign differences between a priori and a posteriori information at output of component decoder 2.

In this paper, an iteration termination technique for turbo decoding at low and high SNR conditions is proposed. This technique is based on monitoring absolute value of mean of the extrinsic information over a frame at the output of two component decoders.

Paper organization is as follows: Section 2 summaries turbo code principles and iterative turbo decoding relevant to the proposed technique. Section 3 deals with analysis and challenges of iteration control in turbo code. Mean based new stopping technique is presented in Section 4. Section 5 shows the simulation results followed by conclusion in Section 6.

2. Turbo Code Principles and Iterative Decoding

Practical codes failed to reach Shannon's capacity limit until the discovery of turbo code in 1990s by Claude

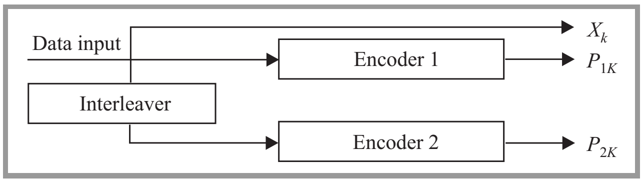

Fig. 1. Generic turbo encoder.

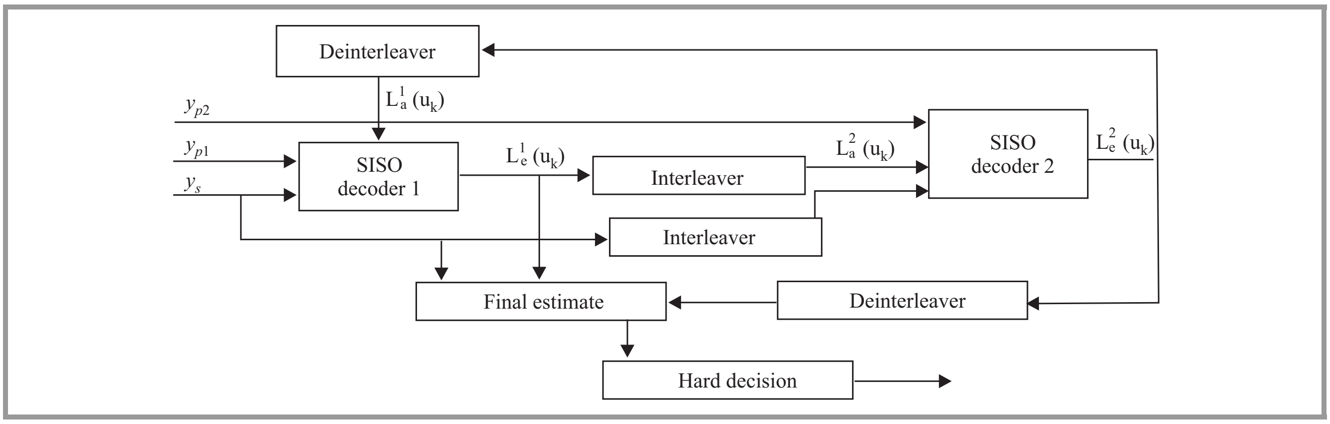

Fig. 2. Turbo decoder.

Berrou *et al.* [14], [15]. Due to its excellent error correction capability, turbo code finds wide applications in mobile communication, short-range communication, deep space communication, and wireless networks [3], [16], [17]. Turbo encoder consists of two Recursive Systematic Convolutional (RSC) encoders separated by an interleaver [12] as shown in Fig. 1. X_k, P_{1k} and P_{2k} are the systematic output, parity check bits 1 of the encoder 1 output, and parity check bits 2 of the encoder 2 output respectively.

RSC encoder 1 has two outputs namely systematic output and parity output. RSC encoder 2 consists of only parity outputs. The presence of interleaver increases codeword weight. If the RSC encoder 1 produces low weight codeword then the probability of producing low weight at the output of RSC encoder 2 is low [18]. The concatenated outcome from the turbo encoder would be a strong one. The data rate can be changed by applying puncturing technique at the output of the encoder.

Turbo decoding takes place by iterative exchange of extrinsic information [19]. The heart of the turbo decoder is the SISO decoder. Maximum A Posteriori (MAP) algorithm is the most commonly used, which outperforms other SISO algorithms under low SNR conditions [18]. The effectiveness of performance depends on the iteration of MAP algorithm on each received code. MAP algorithm calculates A Posteriori Probability (APP) values for each information bit. However, the computational complexity associated with the MAP algorithm is extremely high [20]. Log MAP and Max Log MAP algorithms are two variants of MAP algorithm with reduced computational complexity [21].

The basic iterative turbo decoding architecture is shown in Fig. 2. The input to the component decoders: SISO decoder 1 and SISO decoder 2 are the received systematic information, parity received information and a priori information. Based on the information available at the input of component decoders, the extrinsic a posteriori L values are generated. In the first iteration the input to the SISO decoder 1 – the received systematic and parity information-generates extrinsic a posteriori information $L_e^1(u_k)$ for the received sequence. Extrinsic information generated by the first decoder serves as the a priori information to the second decoder. A priori information, $L_a^1(u_k)$ is zero for the first iteration of SISO decoder 1.

The inputs to the SISO decoder 2 are the received parity information, interleaved systematic bits and a priori information. Decoder 2 generates the extrinsic a posteriori L values, $L_e^2(u_k)$ corresponding to the inputs received. In the subsequent iterations, SISO decoder 1 receives the a priori information corresponding to the de-interleaved extrinsic a posteriori L information from decoder 2. Log-MAP algorithm has been considered in this work for implementing turbo codes, since it is less complex than MAP algorithm and has better performance than Max Log MAP algorithm [20]. Turbo decoder calculates Log Likelihood Ratios (LLRs) for each data bit and after a certain number of iterations, hard decisions are estimated based on the LLR values. The process for calculating LLR values is as follows [21]. The branch metric values are calculated from the received information and extrinsic information of the previous component decoder according to Eq. (1). Let $u = [u_1, u_2, \ldots, u_n]$ be the data sequence, which is encoded and transmitted through a channel. The corresponding received data sequence is $y = [y_1, y_2, \ldots, y_n]$. Then the branch metric values are given by:

$$\gamma_k(s', s) = \frac{u_k(L_a^i(u_k))}{2} + \frac{L_c \sum\limits_{i=1}^{n} y_{kl}u_{kl}}{2}, \tag{1}$$

where L_c is the channel reliability factor, s' and s represent the previous state and present state respectively. The forward metric α and backward metric β are calculated as follows:

$$\alpha_{k+1}(s) = \ln \sum e^{\gamma_k(s', s)+\alpha_k(s')}, \tag{2}$$

$$\beta_k(s') = \ln \sum e^{\gamma_k(s', s)+\beta_{k+1}(s)}. \tag{3}$$

Extrinsic information at the output of component decoders can be calculated as in Eq. (4),

$$L_e^i(u_k) = \ln\left(\frac{\sum_{(s', s)\in\Sigma_k^+} e^{\frac{L_c}{2}y_{pk}p_{lk}+\alpha_k(s')+\beta_{k+1}(s)}}{\sum_{(s', s)\in\Sigma_k^-} e^{\frac{L_c}{2}y_{pk}p_{lk}+\alpha_k(s')+\beta_{k+1}(s)}}\right). \tag{4}$$

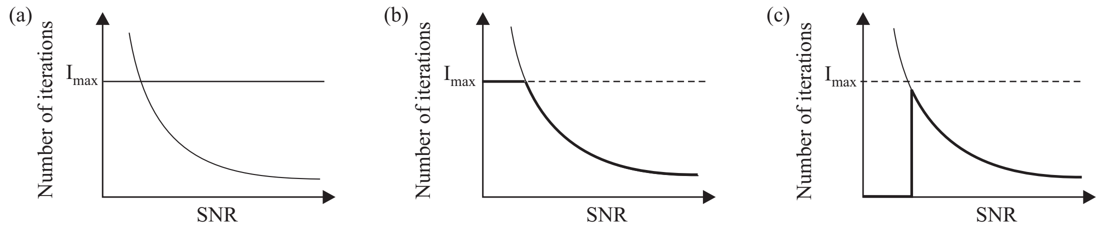

Fig. 3. Average number of iteration required with: (a) fixed iteration termination, (b) termination at high SNR, (c) terminating at low and high SNR.

The LLR at the output of decoder can be computed from the extrinsic information of the component decoders and the received systematic information. LLR values $L_1^i(u_k)$ and $L_2^i(u_k)$ from SISO decoder 1 and decoder 2 can be calculated as in Eqs. (5) and (6) respectively:

$$L_1^i(u_k) = L_{e2}^{i-1}(u_k) + L_{e1}^i(u_k) + L_c y_{uk}\,, \tag{5}$$

$$L_2^i(u_k) = L_{e1}^i(u_k) + L_{e2}^i(u_k) + L_c y_{uk}\,. \tag{6}$$

Each component decoder generates extrinsic information for the next decoder until the maximum number of iteration is reached. After completing the final iteration, hard decisions are made from the output of decoder 2 after deinterleaving.

3. Iteration Control in Turbo Code – Analysis and Challenges

Turbo code achieves excellent performance at the cost of high computational complexity and power. Each iteration consumes a large amount of energy for computations and memory requirements. Computational complexity in the circuit is directly related to the power consumption [22] and functionality is limited by the available power in resource-constrained networks. Computational complexity of the turbo code can be reduced by reducing the number of iterations. However, reducing the number of iterations affects the performance of the turbo code resulting in a tradeoff between performance and complexity [6]. Depending upon the channel conditions, the performance and the required number of iterations also change [23]. The average number of iterations required for successful decoding versus SNR is shown in the Fig. 3 for different iteration termination schemes. Figure 3a shows the fixed iteration scheme, which uses maximum number of iterations at any SNR. Figure 3b shows the iteration termination at high SNR conditions. Here only a few iterations are required to obtain successful decoding at high SNR conditions. Figure 3c indicates the optimized termination technique that considers termination at low and high SNR conditions.

Figure 4 shows the performance of turbo decoding with Log Map algorithm over Additive White Gaussian Noise (AWGN) channel with Binary Phase Shift Keying (BPSK) modulation. From the figure, it is seen that though turbo code performance improves with iteration, at low SNR conditions the improvement is not significant even after the 15-th iteration. It is also observed that at high SNR conditions there is no significant improvement in performance after few iterations.

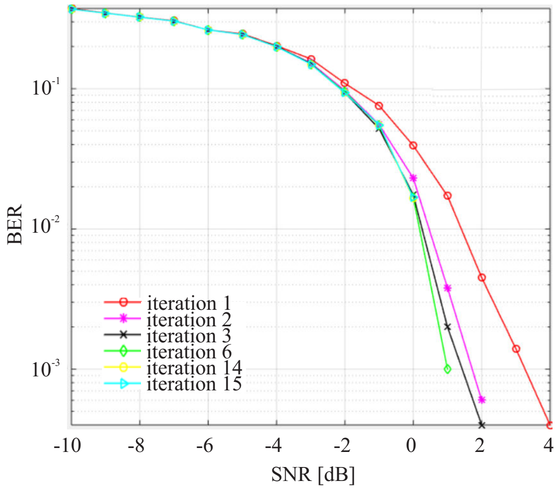

Fig. 4. SNR versus BER performance of turbo code. (See color pictures online at www.nit.eu/publications/journal-jtit)

The challenge is to determine the proper time when further iteration provides no or little improvement in performance. The technique used for this is called the early termination technique. While most of the cases require a few iteration to achieve acceptable performance, undesirable channel conditions require more iteration to achieve an acceptable performance [24]. Sometimes it is observed that although the errors are reduced to acceptable level after a few iterations, errors appear to increase again after some additional iteration. This is because of the numerical errors accumulating in the algorithm with iterations [9]. Figure 5 shows the performance of turbo decoder that accumulates errors with iterations.

From these observations, it is clear that the best performance and computation complexity reduction can be obtained if the iteration is stopped at the proper time. The objective of the early termination technique is to stop the iterations to avoid additional computations that contribute little or no improvement.

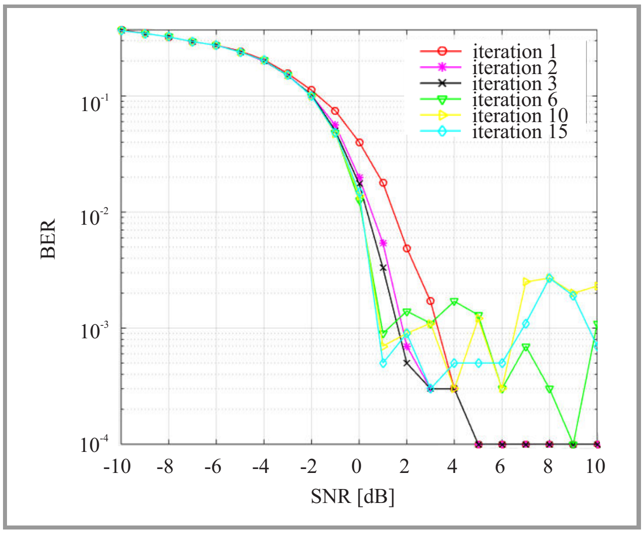

Fig. 5. Turbo decoding performance with accumulation of errors.

Several methods have been introduced by researchers to stop the termination early by considering some objectives like maintaining performance close to that of fixed iteration technique, and reducing power consumption and computational complexity [25]. Efficient iteration control has many advantages such as [6]:

- decoding more number of data blocks and hence improving the throughput,
- reducing the decoding delay,
- reducing the computational complexity,
- improving the performance by reducing accumulation of errors,
- reducing power/energy consumption.

Real time applications and multimedia transmission require systems with low latency and reduced complexity without performance degradation. In resource constrained networks functionality is limited by the stringency in available power [26]. Turbo decoder consumes large part of energy due to the computations associated with the iterations.

Stopping rules are mainly based on hard decision, soft decision, and extra checking categories [22], [27]. In the Cross Entropy (CE) based termination technique, the CE between log likelihood ratios at the output of component decoders at each iteration is calculated [28], [29]. Iteration is terminated if the CE $T(i)$ satisfies the condition: $T(i) < (10^{-2} - 10^{-4})T(1)$. SCR [8] approach is based on the number of sign changes in the extrinsic information between two consecutive iterations. Here the iteration is terminated if the number of sign changes $C(i)$ satisfies the condition: $C(i) \leq (0.05 - 0.3)N$. In SDR [12], [13] technique the iteration is terminated if the number of sign differences $D(i)$ between a priori and a posteriori information satisfies the condition: $D(i) \leq (0.001 - 0.01)N$. ME [9] technique is based on calculating the mean of absolute values of LLRs and stopping the iteration when the mean value is greater than a predefined threshold. Mean reliability based stopping rule has been proposed in literature [10], [11]. In this approach if the mean of absolute values of log likelihood ratios does not change between two consecutive iterations, then the process is terminated. Early iteration termination of turbo code based on histogram method uses LLR metric [20] where iteration is terminated if the central bin of the histogram is zero. In HDA [8] based stopping technique which uses the hard decision from the LLR values, the iteration is terminated if the hard decision values between two consecutive iterations are same.

Many channel conditions require only a few iterations to decide on the decoded bits, but few channel conditions require more iteration. CE, SDR, ME and histogram techniques are applicable to terminate iteration at high SNR conditions whereas SCR and HDA methods are applicable at both low and high SNR and require minimum of two iterations to make a decision even at high SNR. In SDR and CE techniques the data from both the component decoders is required instantaneously to make a decision, so the half iteration technique is not possible in such cases. In mean reliability technique, mean of the absolute values of LLR between iterations is equal at low SNR conditions. Hence, it is applicable to terminate the iteration at low SNR conditions. Techniques which reduce computations as much as possible while maintaining the acceptable performance, capable of saving half iteration computations and stopping the iteration at low and high SNR conditions at proper time still remain a challenge.

4. Mean Based New Stopping Criterion

The excellent performance of turbo code is due to the iterative exchange of extrinsic information. The magnitude of extrinsic information which depends on the channel characteristics (SNR) influences the calculation of branch metrics, forward metrics, backward metrics and LLR values as given in Eqs. (1)–(6). The final output decision is influenced to a very large extent by the extrinsic information. During the processing at the component decoders, the a priori information changes between iterations while systematic and parity inputs remain the same. Based on the mean value of extrinsic information at the output of component decoders an early iteration technique is proposed in this paper. This technique continuously monitors the extrinsic information at the output of component decoder. After each iteration, mean of extrinsic information is calculated. If the mean value is greater than a predefined threshold or if the difference in mean value between iterations lies within a threshold, the iterative process is terminated. The fact that the magnitude of extrinsic information varies with SNR and iteration number is shown in Figs. 6 to 9 as variations of the extrinsic information for low and high SNR at first iteration and fifteenth iteration. The variations are shown for frame size of 10,000 at first and fifteenth iteration for SNR of –5 dB and 5 dB at the output of the two component decoders.

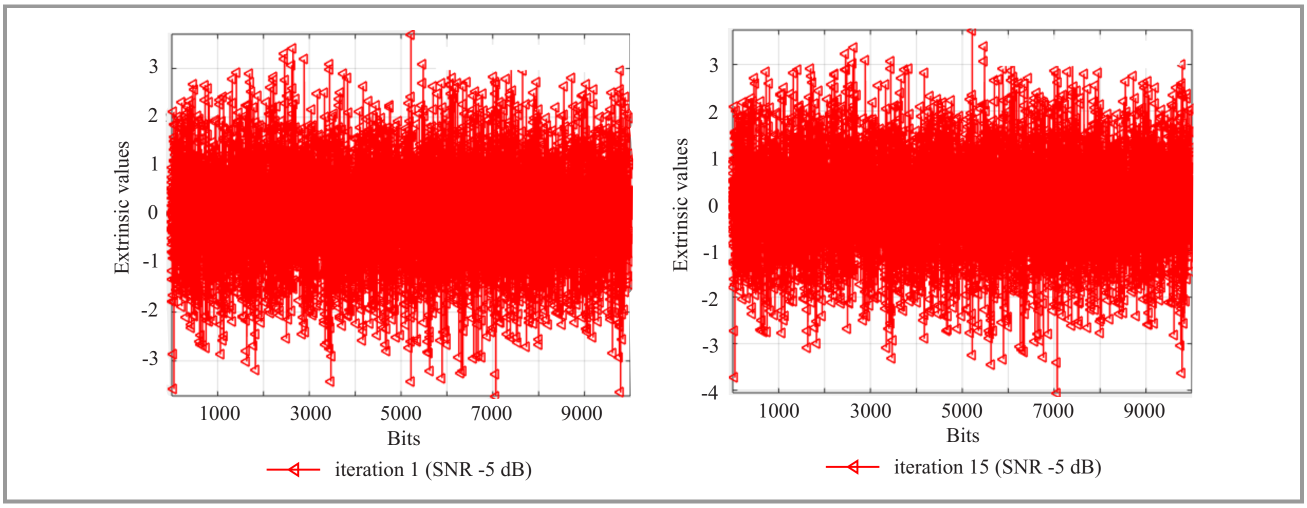

Fig. 6. Extrinsic values at the output of component decoder 1 at –5 dB.

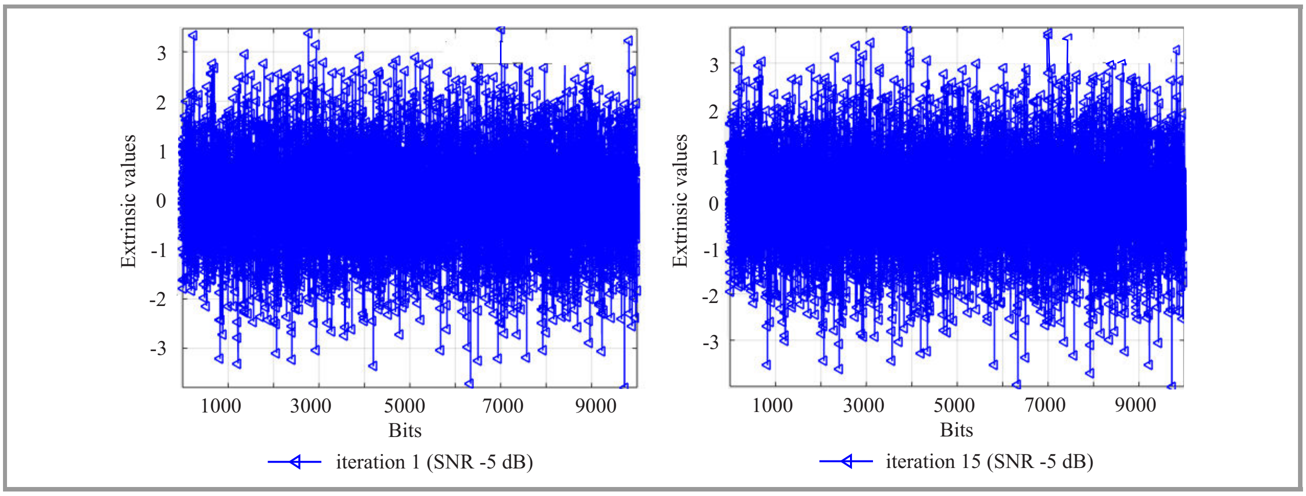

Fig. 7. Extrinsic values at the output of component decoder 2 at –5 dB.

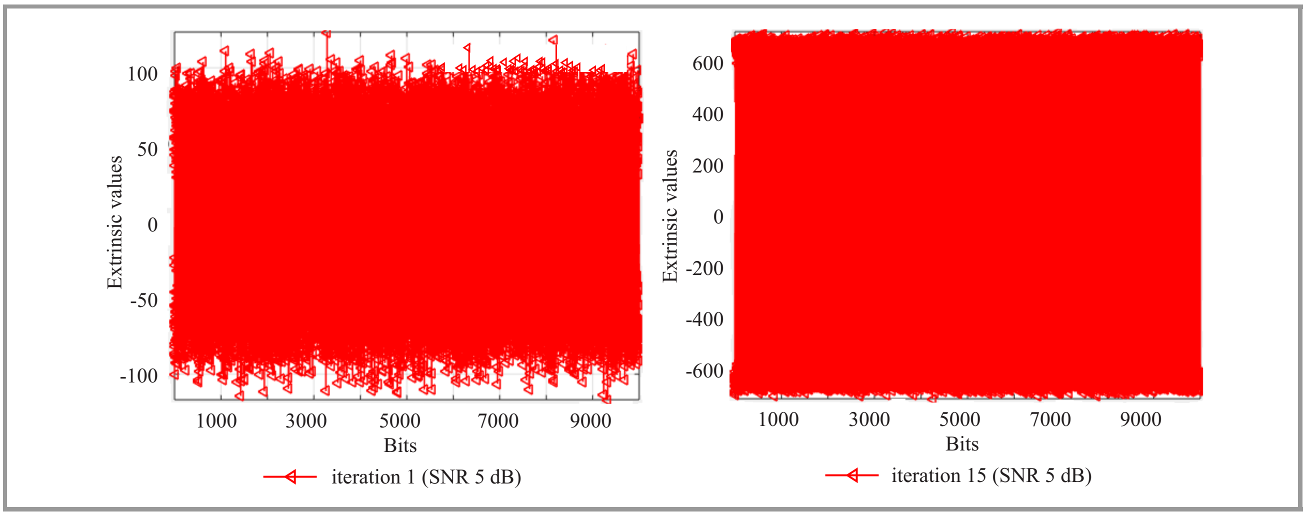

Fig. 8. Extrinsic values at the output of component decoder 1 at 5 dB.

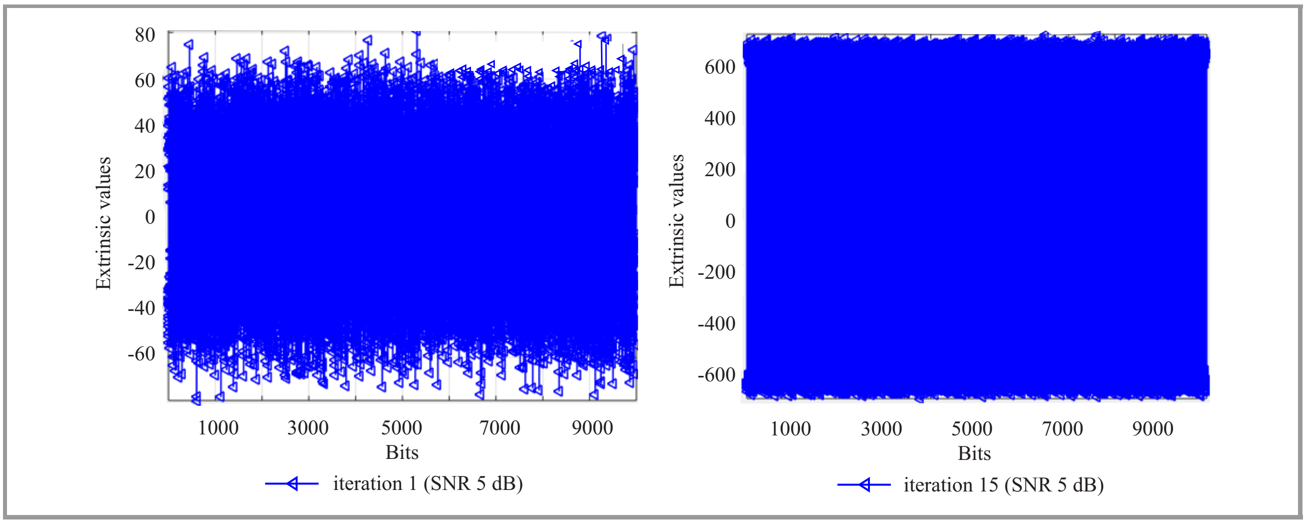

Fig. 9. Extrinsic values at the output of component decoder 2 at 5 dB.

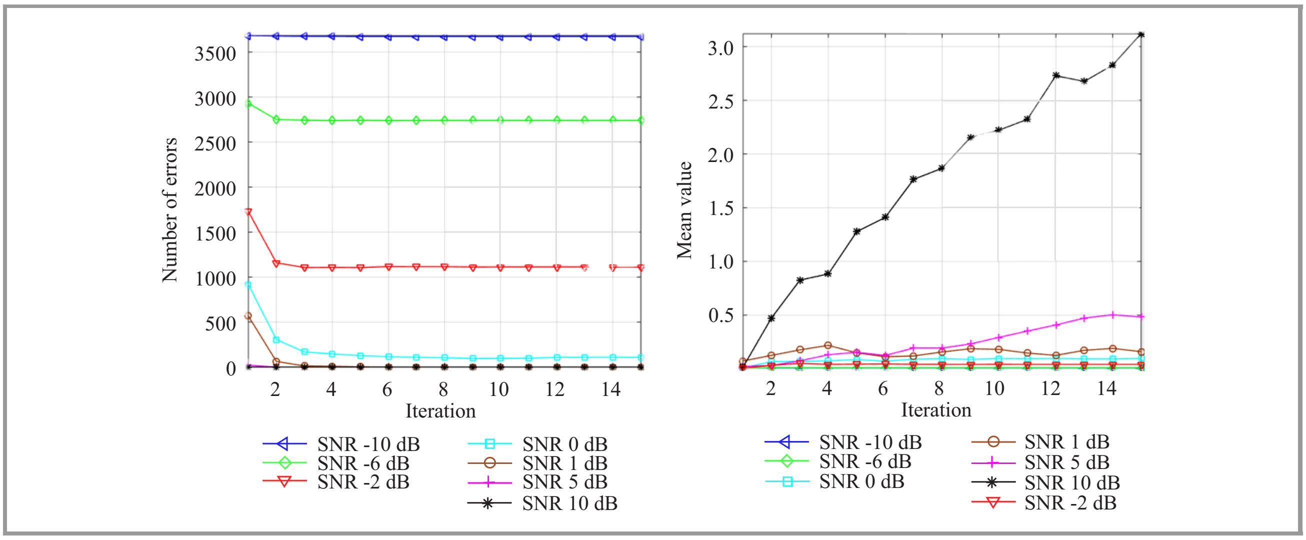

Fig. 10. Analysis of number of errors and absolute value of mean varying with iterations at decoder 1.

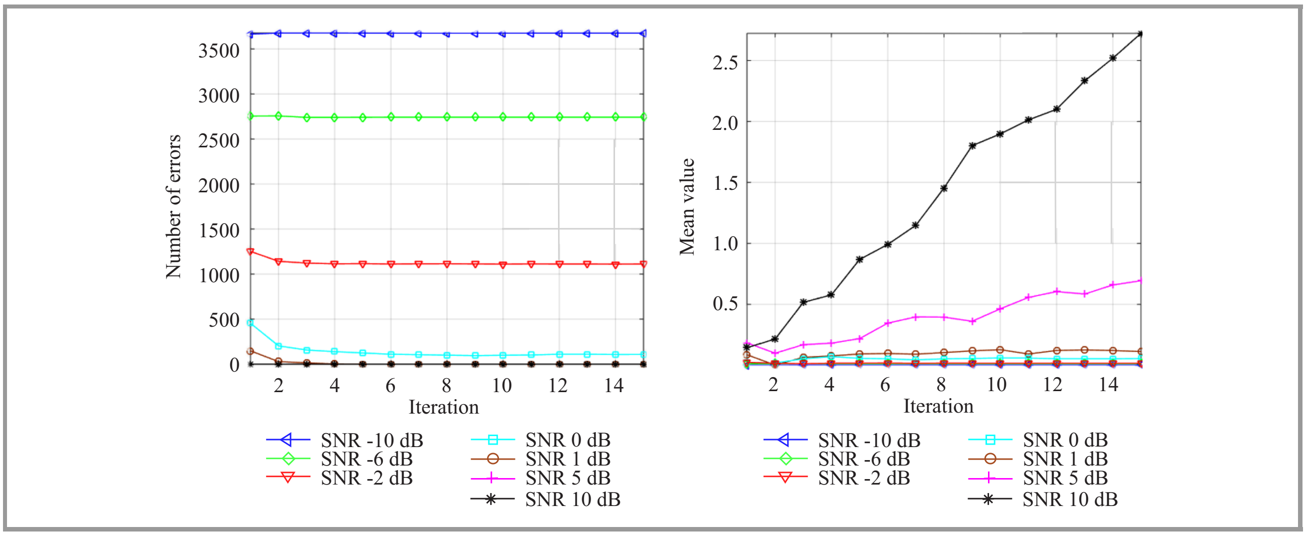

Fig. 11. Analysis of number of errors and absolute value of mean varying with iterations at decoder 2.

A two state turbo code with generator polynomial $[1, \frac{1}{1+D}]$, overall coding rate of $\frac{1}{3}$ and random interleaver is considered. It can be observed from the figures that for low SNR the extrinsic values at the output of the two component decoders are almost constant from first iteration to the maximum iteration number of 15. It can also be seen that the extrinsic values increase for high SNR from first iteration to the maximum iteration number of 15. Extrinsic information calculated at each decoder serves as the a priori information for next component decoder, which in turn uses the extrinsic information for calculation of the branch metric. It can be seen from Eq. 1 that the branch metric is computed by adding the a priori information and channel reliability. Branch metric calculation is dominated more by the higher magnitude extrinsic information. At low SNR the effect of extrinsic values, which serve as a priori information for calculating branch metric values, are negligible. Depending on the channel conditions and errors introduced in the received information, it is either possible to correctly decode before the maximum number of iterations or unable to achieve an acceptable performance even after infinite iterations.

The proposed approach is based on monitoring the absolute value of the mean of the extrinsic information at the output of the component decoders. As the magnitude of extrinsic values changes with iteration and SNR, the mean value also changes correspondingly. Figures 10 and 11 show how the absolute of mean and corresponding errors vary with iteration for a frame size of 10,000.

A close examination of the simulation results presented in Figs. 6 to 11 show that in most of the cases same BER is achieved from the output of the two component decoders after the first few iterations. It can also be seen that many cases require only two iterations to decode correctly since no improvement is observed beyond that. At high SNR conditions, the mean value increases with iterations and requires only a single half iteration or single iteration to correctly decode the sequence. It is also observed that at low SNR conditions, the mean value is almost constant between iterations and the performance improvement is negligible between first and last iteration. In general, the desired output may be reached at the outputs of both the component decoders well before the fixed number of iterations or never reached even after infinite iterations. Based on this analysis, authors propose a new early iteration termination technique for low and high SNR conditions. It utilizes the half iteration termination technique, which reduces the additional computational complexity.

The technique calculates the mean of the extrinsic information at the output of component decoders and compares the absolute value of mean at iteration i with a predefined threshold as in Eq. (7):

$$\text{abs}\big(Mean(i)\big) \geq Th1\,. \tag{7}$$

If the condition in Eq. (7) is satisfied, the iteration is terminated, else it compares the absolute value of mean at iteration i with the mean values of previous iterations as in Eq. (8):

$$\text{abs}\big(Mean(i) - Mean(i-1)\big) \leq Th2\,. \tag{8}$$

If the condition in Eq. (8) is satisfied, the iteration is terminated. The Algorithm 1 shows the proposed technique.

Algorithm 1: Proposed technique

```
Initialization: $i = 1$; stop $= 1$; set imax
while stop or $i \leq$ imax
    Perform the $i$-th iteration for component decoder 1
    Calculate Mean1
    if abs($Mean1(i)$) $\geq$ Th1
        stop $= 0$
    end if
    if $i > 1$ && abs($Mean1(i) - Mean1(i-1)$) $\leq$ Th2
        stop $= 0$
    end if
    Perform the $i$-th iteration for component decoder 2
    Calculate Mean2
    if abs($Mean2(i)$) $\geq$ Th1
        stop $= 0$
    end if
    if abs($Mean2(i) - Mean2(i-1)$) $\leq$ Th2
        stop $= 0$
    end if
    $i = i + 1$
end while
Final output
```

5. Simulation Results

Simulation results for the proposed extrinsic mean based iteration stopping technique for turbo code are presented here. Simulations were performed on turbo code transmitted over AWGN channel with BPSK modulation with the maximum number of iterations set to 15. A two state turbo code with generator polynomial $\left[1, \frac{1}{1+D}\right]$,

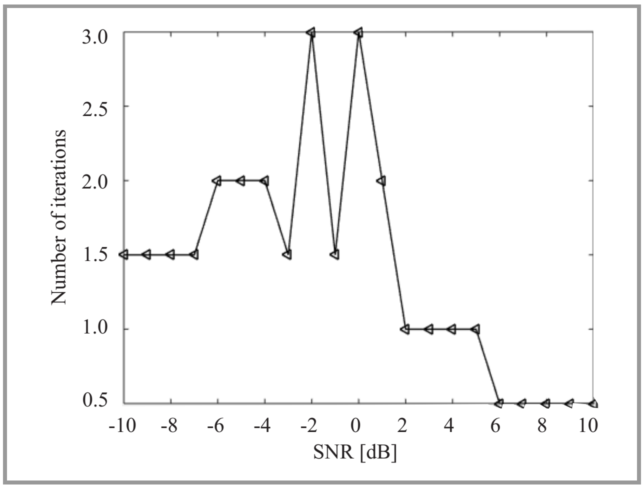

Fig. 12. Number of iterations as a function of SNR.

overall coding rate of $\frac{1}{3}$ and random interleaver is considered. The performance and complexity trade off depend on the threshold values. The threshold values selected are as $0.15 \leq \text{Th1} \leq 0.5$ and $0 \leq \text{Th2} \leq 0.001$. The number of iterations required for different values of SNR are shown in Fig. 12 for a frame size of 10,000 and Th1 = 0.3 and Th2 = 0.0009. As the decoding iterations come down the resulting overall computational reduction leads to a considerable power saving. Thus, the proposed algorithm terminates the unnecessary iterations and reduces both decoding delay and power consumption. The performance analysis of the proposed technique is shown in Fig. 13.

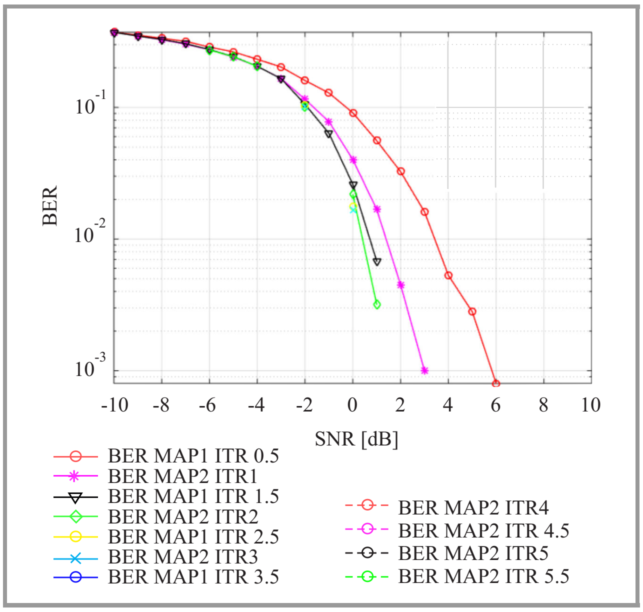

Fig. 13. SNR versus BER performance of the proposed technique.

The performance comparison of the proposed technique with histogram technique, SCR, mean reliability, ME, SDR, fixed iteration and HDA is shown in Fig. 14. Figure 15 shows the corresponding average number of iterations required as a function of SNR. It is observed from the simulation results that the effect of proposed algorithm on turbo decoder helps to reduce decoding delay, computations and thus power consumption. As expected, performance and required number of iterations change with the threshold value. From the simulation results, one can see that proposed technique achieves performance close to that of fixed iteration technique. It is clear that the scheme is able to terminate early for low and high SNR and also able to potentially save half iterations.

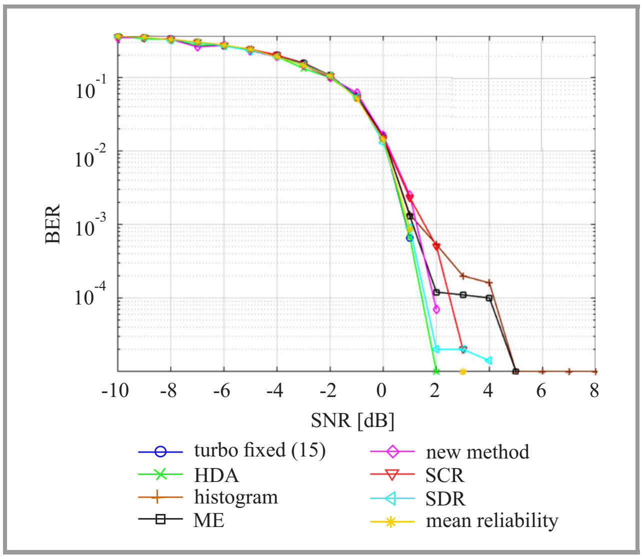

Fig. 14. Comparison of SNR versus BER performance.

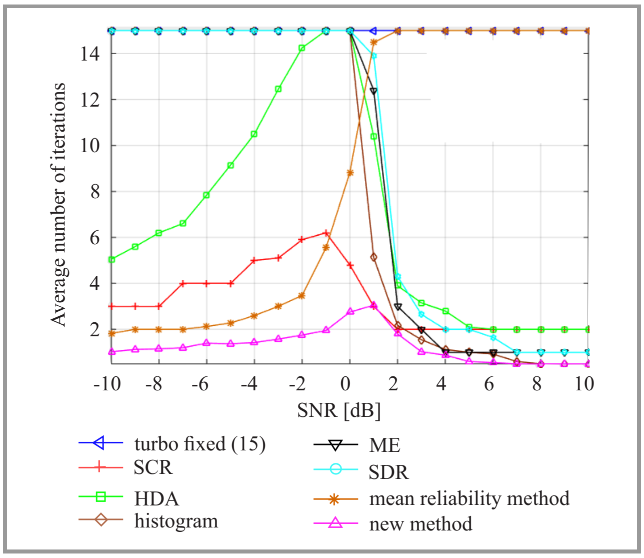

Fig. 15. Comparison of SNR versus average number of iterations.

Computational time and average number of iterations is reduced as compared to the already available techniques. The proposed early termination technique is appropriate for wireless communication systems requiring shorter latency and low power consumption. Table 1 shows the computational time required for the different stopping techniques with maximum iteration kept as 15, SNR from –10 to 10 dB and for a frame size of 10,000 when run on Intel Core i5-4690S @ 3.20 GHz with 64 bit Windows operating system.

Table 1
Computation time comparison

Algorithm	Computation time for 15 iteration and SNR: –10…10 dB
Fixed iteration method	37.22 s
Histogram technique	20.50 s
Sign Difference Ratio	21.93 s
Mean estimate	22.39 s
Mean reliability	24.89 s
Sign Change Ratio	7.811 s
Hard Decision Aided	16.94 s
Mean based new stopping method	**4.57 s**

6. Conclusion

Turbo code achieves significant error correction capability in wireless channel at the cost of computational complexity. A new stopping criteria based on the absolute mean value of extrinsic information is proposed in this paper. Performance is analyzed in terms of BER, average number of iterations and average computation time. The analysis shows that the proposed method can reduce the average number of iterations and decoding delay as compared to other techniques. The method is equally effective at high as well as low SNR conditions in reducing the number of required iterations. It takes advantage of the half iteration but with negligible performance degradation as compared to fixed iteration termination scheme. Average iteration number reduction leads to corresponding power saving, reduction in decoding delay and throughput improvement by decoding more number of data blocks. In the proposed technique, depending on the choice of threshold value, there is a trade-off between performance and complexity of operation. The performance improvement achieved in terms of BER, iteration number, and processing time, makes the proposed method really attractive for systems requiring low latency, low power consumption and better performance in terms of error correction.

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P. Salija received her B.Tech. degree in Electronics and Communication Engineering in 2011 from Cochin University of Science and Technology and M.Tech. degree in Communication Systems in 2013 from Karunya University. She is currently a Ph.D. student in the Department of ECE at Amrita School of Engineering. Her current research interest is error control coding in wireless systems.

E-mail: p_salija@cb.amrita.edu
Department of Electronics
and Communication Engineering
Amrita School of Engineering, Coimbatore
Amrita Vishwa Vidyapeetham
Amrita University India

B. Yamuna – for biography, see this issue, p. 112.