LETTER

A Low-Complexity Stopping Criterion for Iterative Turbo Decoding

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SUMMARY This letter proposes an efficient and simple stopping criterion for turbo decoding, which is derived by observing the behavior of log-likelihood ratio (LLR) values. Based on the behavior, the proposed criterion counts the number of absolute LLR values less than a threshold and the number of hard decision 1's in order to complete the iterative decoding procedure. Simulation results show that the proposed approach achieves a reduced number of iterations while maintaining similar BER/FER performance to the previous criteria.

key words: *iterative decoding, stopping criteria, turbo decoder*

1. Introduction

Turbo codes [1] have been proved as one of the most powerful solutions for the forward error correction. As shown in Fig. 1, the turbo decoder consists of two component decoders and operates iteratively to produce improved soft outputs by using the outputs of the other component decoder. As the number of iterations is directly related to decoding latency and power consumption, many stopping criteria (e.g. [2]–[5]) have been proposed to terminate the decoding procedure early based on the observation that no more performance improvement is achieved after a certain number of iterations. The stopping criteria should lead to a small number of iterations with negligible BER degradation and must be simple enough to be implemented with low complexity. In [2], two criteria called hard-decision-aided (HDA) and sign-exchange-ratio (SCR) are derived from the cross-entropy (CE) [3] by applying some modifications. These criteria are effective in reducing the number of iterations but require an additional memory of frame size. More efficient criteria such as sign-different-ratio (SDR) [4] and mean-estimate (ME) [5] are proposed to control the number of iterations with less complexity overhead.

As the turbo codes are employed in wireless applications such as W-CDMA and CDMA-2000, efficient stopping criteria are still required to reduce power consumption. In this letter, we present a new stopping criterion that is as simple as SDR and ME but can achieve a smaller number of iterations without degrading error-correcting performance. The proposed criterion is derived by observing the behavior of log-likelihood ratio values.

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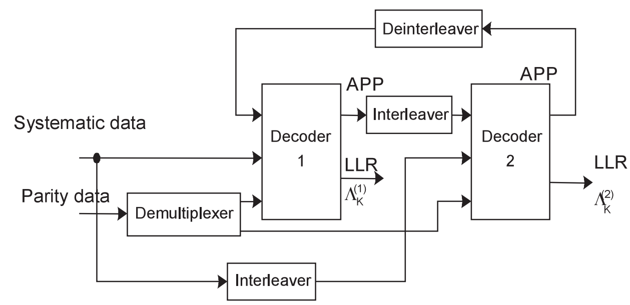

Fig. 1 Structure of a turbo decoder.

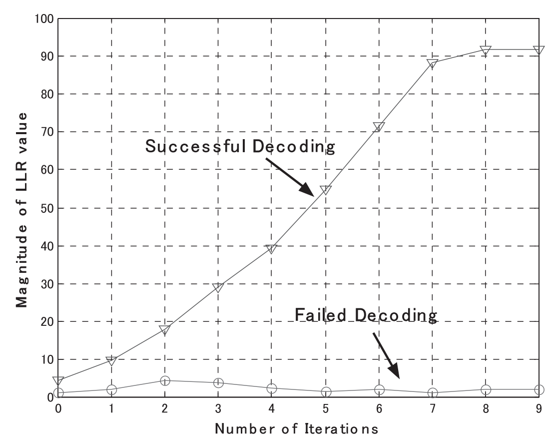

Fig. 2 Behavior of LLR values when $E_b/N_0 = 0.4$ dB.

2. Observations on LLR Values

Assuming BPSK transmission over an AWGN channel, let $x_k \in \{-1, +1\}$ and y represent a transmitted bit and the corresponding received signal, respectively. The *a posteriori* probability, $\Pr[x_k = +1|y]$ or $\Pr[x_k = -1|y]$, is the probability that the information bit is 1 or −1 given the received signal y, respectively. Once these probabilities are given, they are transformed into log-likelihood ratio (LLR) values in order to make a decision on a particular symbol. The general LLR form of the k-th bit is

$$\Lambda_k = \ln \frac{\Pr[x_k = +1|y]}{\Pr[x_k = -1|y]} = \ln \frac{\Pr[x_k = +1|y]}{1 - \Pr[x_k = +1|y]}. \quad (1)$$

The absolute value of Λ_k represents decoding reliability, which has a tendency to increase as the decoding is iterated if the decoding is successful as shown in Fig. 2. Otherwise, the value tends to remain in a small magnitude for a failed decoding. Based on this observation, an erroneous symbol can be found by monitoring the number of $|\Lambda_k|$ values smaller than a threshold. The sign value of Λ_k is used to make a hard decision of +1 or −1, and the hard decision of a successfully decoded symbol is not changed after a number of iterations. These two observations on LLR values are used to obtain a new simple stopping criterion.

3. Proposed Stopping Criterion

Based on the observations of Λ_k, a measure for the m-th component decoding of iteration i is defined as

$$f_k = \begin{cases} 1, & \text{if} \quad |\Lambda_k| < T_l \\ 0, & \text{else} \end{cases} \quad , \quad S_i^m = \sum_{k=1}^{N} f_k \tag{2}$$

where N is the frame size, m is 1 or 2 in turbo decoding, and T_l is the threshold value determined by simulation. A higher T_l value makes more confirmed decoding. If S_i^m is less than a given value of T_c, we regard the frame as error free and stop the iterative decoding. As there is a trade-off between the average number of iterations and BER performance, T_c is also determined by simulation. As the measure (2) can miss a few errors, which is sometimes critical especially when the SNR is higher than 1.0 dB, an additional condition is augmented based on the second observation. The condition is to check whether the count of hard-decision 1's in the current component decoding is the same as that of the last component decoding. The count and hard-decision 1's are defined as follows.

$$h_k = \begin{cases} 1, & \text{if} \quad \Lambda_k > 0 \\ 0, & \text{else} \end{cases} \quad , \quad C_i^m = \sum_{k=1}^{N} h_k. \tag{3}$$

Experimental results show that the augmented condition does not increase the average number of iterations noticeably. The proposed stopping criterion summarized below can be implemented with only two counters and one comparator.

Step 1: Set T_l and T_c to the optimum values obtained from simulation. Initialize C_p to −1, m to 1, and i to 1.
Step 2: Calculate S_i^m and C_i^m by processing the current component decoder.
Step 3: If $S_i^m < T_c$, then go to step 4. Otherwise go to step 5.
Step 4: If $C_i^m = C_p$, terminate the iterative decoding procedure. Otherwise go to step 5.
Step 5: $C_p = C_i^m$, update i or m, and then go to step 2.

As equations (2) and (3) are not related to the position of each bit, it is possible to stop in any component decoder.

4. Experimental Results

To compare the previous stopping criteria and the proposed one, simulations are conducted for the W-CDMA standard over an AWGN channel. The log-MAP turbo decoding algorithm is used for a frame size of 1024 in the simulation. The values of T_l and T_c are determined to 4.0 and 0.01×1024 for $E_b/N_0 < 0.6$ dB and to 8.0 and 0.001×1024 for $E_b/N_0 > 0.4$ dB, respectively. For a high SNR, T_l needs to be increased and T_c is decreased to maintain similar error correcting performance. Note that the SNR regions are overlapped, so that it is not required to employ an exact SNR estimator. In our case, a SNR of 0.5 dB is used to select one of the two sets of T_l and T_c values. Although the previous stopping criteria such as ME and SDR are significantly dependent on the exact SNR value, the proposed criterion is dependent on the SNR regions, thus less sensitive to the exact SNR value.

Figure 3 depicts the average number of iterations obtained for various stopping criteria such as fixed 10 iterations, HDA, SDR, ME and the proposed one. The maximum number of iterations is limited to 10 in the experiment. Thresholds for the ME criterion and the SDR criterion are set to the optimum values presented in [4] and [5]. If the SNR is greater than 0.3 dB, the proposed criterion achieves noticeable improvement over the previous criteria.

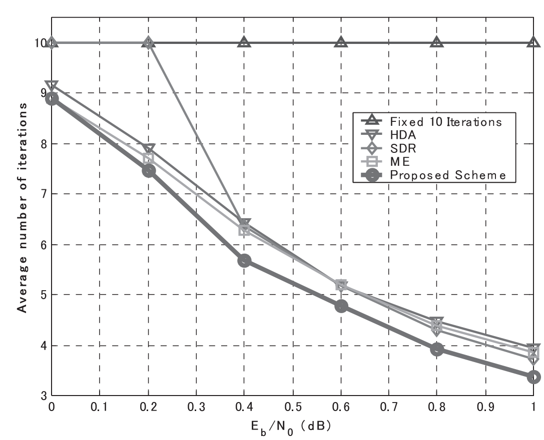

Fig. 3 Average number of iterations measured for 5 stopping schemes with a frame size of 1024.

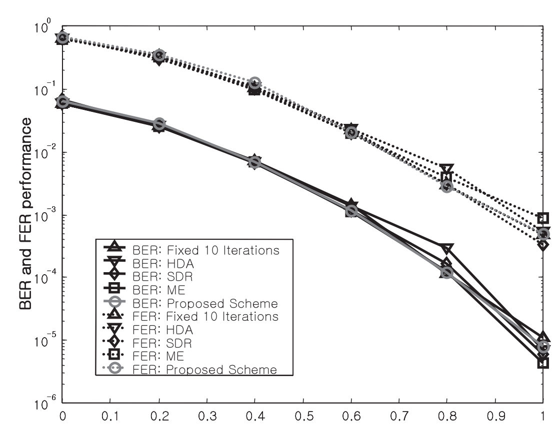

Fig. 4 BER and FER performance meaused for 5 stopping schemes with a frame size of 1024.

On the average, 0.5 iteration is reduced even compared to the SDR and ME criteria that are known to be most efficient previously. Figure 4 shows the corresponding BER and FER performances, which indicates that the proposed method achieves the smallest number of iterations without degrading BER and FER performance for all the cases. The number of iterations reduced by the proposed method becomes more significant if enhanced BER and FER performances obtainable with a large number of iterations are required.

5. Conclusion

An efficient stopping criterion with low computational complexity has been addressed in this letter. It leads to a smaller number of iterations compared to the previous criteria such as HDA, SDR and ME and shows almost the same performance as that of the fixed iterative decoding. The new criterion does not require additional memories, and can be implemented with two counters and one comparator. As the proposed criterion is effective in reducing the number of iterations, it is appropriate for wireless communication systems requiring shorter latency and lower power consumption.

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