

# ENERGY-EFFICIENT TURBO DECODER

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## ABSTRACT

Turbo codes have been recently adopted in the next generation of wideband CDMA standards. These codes achieve superior performance at the expense of high computational complexity. This makes their low energy implementation a very important yet challenging problem. In this paper we study the effect of different approximation techniques such as pruning the trellis, reducing the number of states, sliding window, early termination on the Bit Error Rate (BER) and energy consumption for a Turbo decoder implemented on a general purpose processor. We show that a combination of these techniques can result in 66.5% energy reduction for a log-MAP based Turbo decoder if a loss of 1.4 dB in SNR can be tolerated at  $\text{BER} = 10^{-5}$ .

## 1. INTRODUCTION

The emergence of battery powered hand-held devices as popular computing devices makes reducing the total power consumption without compromising on performance a very important problem. Turbo codes [1] have been recently adopted by 3rd generation mobile standards such as 3GPP and CDMA 2000. The superior performance of Turbo codes is due to the combination of parallel concatenated coding, recursive encoding, pseudo-random interleaving and iterative decoding. All of these factors result in the energy consumption of the coder being very high.

There are two main algorithms for Turbo decoding: the Maximum A Posteriori Algorithm (MAP) and the Soft Output Viterbi Algorithm (SOVA). The SOVA based decoder is computationally less complex since it chooses the branch in the trellis with the highest probability and discards the other. We use bi-directional SOVA in our implementation. MAP, on the other hand, does not reject any path and calculates the probabilities of each point in the trellis. In order to reduce the computational complexity of MAP, it is generally implemented in the logarithmic domain (referred to as the log-MAP algorithm).

In this paper we show how judicious use of approximation algorithms can be used to significantly reduce the energy consumption of the Turbo decoder by reducing the computational complexity of the decoding algorithms (log-MAP/SOVA) with a minimal decrease in the BER. The ap-

proximation techniques that we studied reduce the number of computations by pruning the trellis, terminating the iterations early, applying sliding window and reducing the number of states in the trellis. In each case we compared the performance with respect to BER and energy. Such a study of quality-energy tradeoffs gives the user the flexibility to choose different approximations based on the application requirements. A combination of the approximation techniques resulted in 66.5% energy savings over the log-MAP based Turbo decoder, with a loss of  $\approx 1.4$  dB in SNR for a BER of  $10^{-5}$  when implemented on a general purpose processor. Furthermore, reduced search and pruning techniques result in the largest reduction in energy (20%) with 0.5 dB loss in SNR. A subset of the approximations listed in this paper has been integrated into an ASIC implementation in [2] that resulted in 70% reduction in power consumption over a fixed 6-iteration, 8-state baseline Turbo decoder at 2 dB of SNR. Algorithmic and architectural approaches to reduce the power consumption in the data path have also been proposed in [3].

The rest of the paper is organized as follows. Section 2 gives a brief description of the different energy reduction techniques. Section 3 describes the proposed algorithms and the results of our methods and section 4 concludes the paper.

## 2. ENERGY REDUCTION TECHNIQUES

Though SOVA and log-MAP are low complexity algorithms compared to MAP, they still require a large number of computations. In the rest of this section, we describe existing techniques to reduce the number of computations and their effect on energy consumption.

### 2.1. Experimental setup

In order to calculate the computation power (and energy), we ran the source code on Wattch [4], a framework for architectural level power analysis. All the simulations were performed on rate 1/2 Turbo code with 8 PSK modulation, interleaver size 2048 bits and constraint length ( $K$ ) = 5. The quantitative quality results were obtained in terms of BER measurements. The quantitative estimates for energy values were obtained using Wattch. The processor used in Wattch

is representative of a state of the art general purpose processor and had the following parameters: issue width 4, window size 16, number of virtual registers 32 and number of physical registers 16, data-path width 64, L-1 data cache size 128:32:4 (128K is the data cache size, 32K is the line size and 4 is the set associativity). L-2 data cache 1024:64:1, L-1 instruction cache 512:32:1 and L-2 instruction cache similar to the L-2 data cache.

### 2.2. Reduction in the number of states

In this method the state trellis is reduced to a smaller structure and the search is performed on the reduced trellis. This technique has been applied to MAP in [5] and SOVA in [6]. The energy savings and loss in SNR were 24.5%(25.2%) and 0.51 dB(0.58 dB) for log-MAP(SOVA) at a BER of  $10^{-5}$ .

### 2.3. Reduction in the number of paths

The T and the M algorithms are pruning algorithms that reduce the number of paths in a classical Viterbi algorithm [7]. The pruning algorithm was applied to the trellises of log-MAP and SOVA. The energy savings in log-MAP(SOVA) were  $\approx 25\%$  at the expense of 0.48 dB(0.63 dB) loss in SNR for a BER of  $10^{-5}$ . While the reduced search and the pruning techniques have almost similar quality/energy tradeoffs, pruning is a more effective technique for small values of SNR.

### 2.4. Effects of Stopping Criteria

Since early termination of the iterative decoding helps conserve power, the effects of the following stopping criteria were studied: cross entropy (CE) [8], sign change in the log likelihood and extrinsic informations (LLR) [9] and adaptive iteration based on CRC (CRC)[10]. Fig.1 gives the BER vs SNR, when the three stopping criteria are used for terminating the decoding in log-MAP, Max log-MAP (which is a version of log-MAP, where some additions are approximated by *max* operations) and SOVA. CE is better than LLR and CRC with respect to BER performance. However, as SNR increases to 2 dB, the plots converge. While the three stopping criteria result in similar performance for SOVA, CE clearly outweighs LLR for log-MAP.

Fig.2 gives the energy estimates for all the three decoding algorithms when the above stopping criteria are used. LLR is the best stopping criterion for all the three decoding algorithms with respect to energy consumption. It results in 17.5% energy consumption compared to the CE criterion.

### 2.5. Sliding Window Techniques

Sliding window is a very effective technique to reduce the number of data accesses. By using smaller block size in conjunction with sliding window, one can reduce the memory required to store the state and the branch metrics. In addition, the delay can be reduced if the decoding blocks are synchronized properly. Sliding window techniques with different re-usability factors were studied. In terms of performance and energy, the sliding window with a re-usability

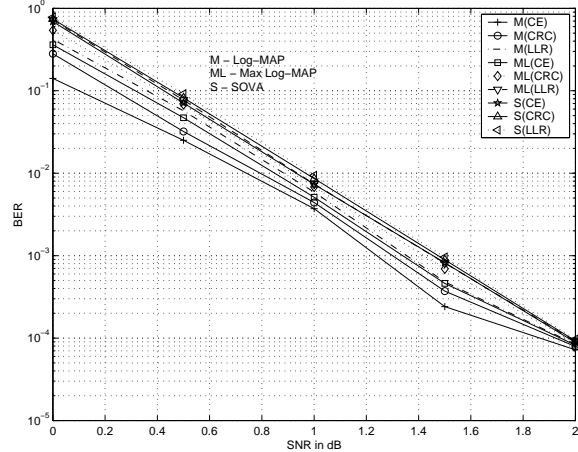


Fig. 1. BER vs SNR for various stopping criteria for log-MAP, Max log-MAP and SOVA

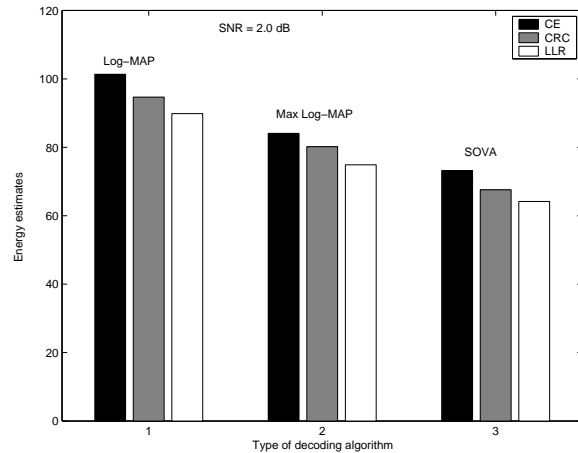


Fig. 2. Energy estimates for log-MAP, Max log-MAP and SOVA for various stopping criteria

factor of 1 (overlap of 1 state) is better than other alternatives (overlap factors of greater than 1). For instance, energy savings of 11.8% was achieved on log-MAP and 12.2% on SOVA at the expense of 0.3 dB and 0.43 dB loss in SNR respectively for a BER of  $10^{-5}$ . When sliding window techniques with higher re-usability factors were used, the loss in SNR was disproportionately high.

### 2.6. Finite Precision Analysis

In [9] finite precision effects on the performance of Turbo decoders have been analyzed. While a large word length results in more storage area and more number of computations, a smaller word length affects performance. Our study showed that 5:2 (5 denotes the total number of bits and 2 is the number of bits for the fractional part) scheme is the best for a log-MAP based decoder and that the 4:3 scheme is the best for a SOVA based decoder. Quantization of extrin-

| Approximation            | Drop in SNR in dB |      | % Energy Reduction |      |
|--------------------------|-------------------|------|--------------------|------|
|                          | Log-MAP           | SOVA | Log-MAP            | SOVA |
| Loop Transformation      | 0.0               | 0.0  | 8.5                | 8.5  |
| Finite Precision Effects | 0.32              | 0.41 | 14.8               | 15.2 |
| Sliding Window           | 0.3               | 0.43 | 11.8               | 12.2 |
| Reduction in paths       | 0.48              | 0.61 | 25.3               | 25.4 |
| Reduction in states      | 0.51              | 0.58 | 24.5               | 25.2 |
| LLR Stopping Criterion   | 0.34              | 0.39 | 17.5               | 18.2 |

**Table 1.** Drop in SNR and energy reduction corresponding to the different approximation techniques

sic information has also been dealt with in [9]. In terms of extrinsic information, 5:3 and 5:1 schemes are the best for log-MAP and SOVA based decoders. Watch results indicate energy savings of around 14.8%(15.2%) for log-MAP (SOVA) based decoders at the cost of 0.32 dB(0.41 dB) drop in SNR for a BER of  $10^{-5}$ .

### 2.7. Loop Transformations

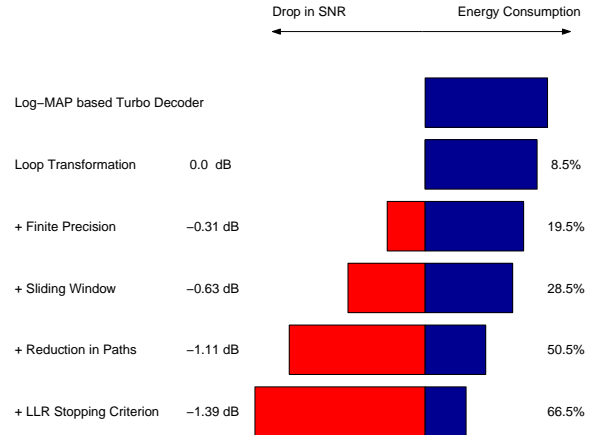
Data loop transformations are high level transformations and can be applied on top of all the above approximations. Application of loop unrolling on the C-code of log-MAP and SOVA resulted in energy savings of 8.5%.

### 2.8. Summary

In Table 1, the drop in SNR (in dB) and the percentage energy reduction (w.r.t log-MAP and SOVA) for a block size of 2K and BER of  $10^{-5}$  have been shown for each of the approximation techniques. The highest energy savings are obtained from reduction in number of paths and reduction in number of states. Loop transformations result in energy savings with no loss in quality. A combination of these approximation techniques can be used to match the specification of different applications with different energy-quality requirements.

## 3. RESULTS

Fig.3 describes the energy savings and loss in SNR in dB for a BER of  $10^{-5}$  when a combination of approximations is applied for a log-MAP based decoder. Such a figure can be used to choose the approximations based on the application requirements. For instance, in applications where quality is of utmost concern, we can apply data loop transformations and finite precision effects (0.31 dB loss and 19.5% energy savings). In applications where power or battery life is more important, all of the approximations can be used. This would result in 1.4 dB loss with 66.5% energy savings as shown in Fig.3. For applications where one desires to have a reasonable performance ( $< 0.7$  dB loss) a combination of data loop transforms, finite precision effects and sliding window can be used (30% energy savings). For applications where one desires less than 1 dB loss in SNR and still achieve significant energy savings (50%), a combina-

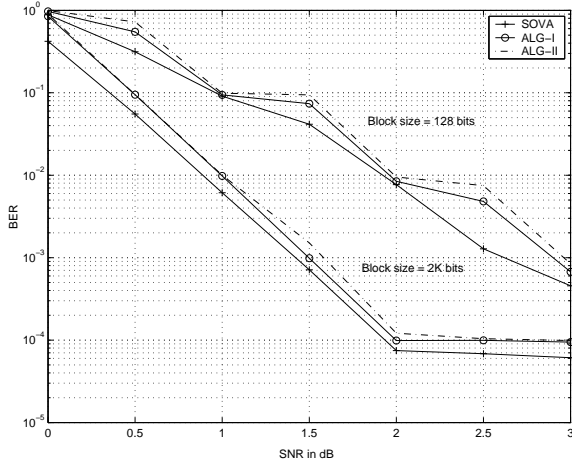


**Fig. 3.** Distribution of energy savings in log-MAP based Turbo decoder at BER of  $10^{-5}$  and block size = 2K

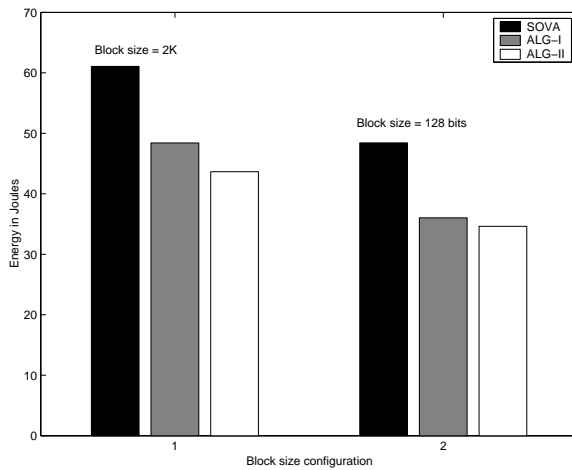
tion of data loop transforms, finite precision effects, sliding window and LLR stopping criterion can be used.

A point to be noted is that the drop in SNR is not additive for successive approximations. For instance, if only sliding window technique or only finite precision technique are applied separately on the log-MAP based Turbo decoder, the drops in SNR are 0.45 dB and 0.35 dB respectively. But when both the techniques were applied simultaneously, the drop in SNR is found to be 0.63 dB. Next, the two most promising techniques, namely, reduction in the number of paths and reduction in the number of states are compared w.r.t quality and energy consumption for different block sizes.

Consider two implementations (which use loop unrolling, finite precision effects, sliding window and LLR stopping criterion) but differ in whether the approximation reduction in the number of paths (ALG-I) or reduction in the number of states (ALG-II) is applied. We do not consider an implementation where both reduction in the number of paths and reduction in the number of states is applied since the SNR drop is excessively high ( $\approx 0.8$  dB). Fig.4 gives the plot of BER vs SNR for the two proposed implementations and SOVA for two different block sizes (128 bits and 2K bits).



**Fig. 4.** BER vs SNR for the two implementations and SOVA for two block sizes



**Fig. 5.** Energy estimates of the two implementations and SOVA at 2 dB SNR

While a block size of 128 bits is suitable for voice applications, a block size of 2K bits is suitable for data applications. For smaller block sizes, we observe that ALG-I has a better performance than ALG-II. For large block sizes, both the approximations are close in terms of performance. Fig.5 gives the energy estimates for ALG-I, ALG-II and SOVA. ALG-II has lower energy consumption for both block sizes. For smaller block sizes, ALG-II result in 32% energy savings where as for large block sizes, the approximations result in 27% energy savings with respect to SOVA.

#### 4. CONCLUSIONS

In this paper we showed the effect of applying different approximation techniques on the BER and energy consumption of a Turbo decoder. We found that reducing the number of paths and reducing the number of states are the most ef-

fective techniques in terms of reducing energy consumption and should be a part of any low-power Turbo decoder implementation. The energy-quality tradeoff study presented here will help the user to choose an algorithm configuration that matches the application requirement. More sophisticated algorithms that provide better and wide ranging quality/energy tradeoffs for different channel environments are a subject of future work.

#### Acknowledgements

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#### 5. REFERENCES

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