A Review of VLSI Applications of Error Detection and Correction Codes

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Abstract: Turbo codes have become an active area of research owing to the fact that they come closest to the Shannon's limit for codes. This paper presents a comprehensive survey on turbo codes. The paper begins with an introduction of turbo codes followed by its applications and advantages. Subsequently, prominent work in the field is cited in brevity as literature review. The various approaches of the work have been exemplified. Finally a conclusion is presented pertaining to the topic. It is expected that the paper will render useful insights into the functioning and utility of turbo codes.

Keywords: Very Large Scale Integration (VLSI), System on Chip (SOC), Turbo Codes, cascaded code blocks, recursive decoding, puncturing, bit error rate.

I. INTRODUCTION

Turbo codes are often viewed as a parallel concatenation of convolution codes. They are of great interest as they come very close to the Shannon's limit. The aim of channel coding is often to enhance reliability of communication even at low values of signal to noise ratio. One of the major challenges is to evade the conflict of randomness and complexity of code design. Turbo codes can be visualized as a parallel concatenation of convolution codes and generally render exceptionally good BER performance at low SNR values.[11] The codes exhibit very good performance for both AWGN and Rayleigh channels in terms of approaching the Shannon's limit. Interleaving is used to render randomness to the code and it follows a concatenated structure. In general Turbo Codes are very close to Shannon's limit mathematically defined as:

$$C = Blog_2(1+\frac{S}{N}) \quad (1)$$

Here,

C is channel capacity
S is signal power
N is noise power
B is bandwidth

The Shannon's limit is BER of almost 10^{-5} (ideally 0) for $\frac{E_b}{N_0}$ = 0 dB for binary modulation. [11]
The above limit corresponds to a binary rate R=1/2 convolution encoder which has a constraint length K and memory M=K-1.
Assuming that the bit d_k is the input to the encoder at time k, we have the codeword C_k which is binary coupled:

$$X_k = \sum_0^{k-1} g1_i d_{k-1} \text{ mod.2 } g1_i = 0,1 \quad (2)$$

$$X_k = \sum_0^{k-1} g2_i d_{k-1} \text{ mod.2 } g2_i = 0,1 \quad (3)$$

Where,

$$G_1: \{g_{1i}\} \quad (4)$$
$$G_2: \{g_{2i}\} \quad (5)$$

G1, G2 are two code generators generally expressed in the octal form.
The Convolutional encoders are used in a parallel structure with an interleaver to introduce randomness. The following diagram exhibits the structure of the coding mechanism

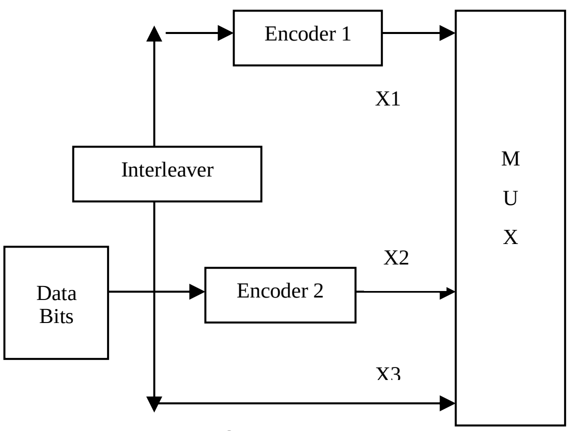

Fig.1 Structure of Turbo Code Encoder [11]

The first encoder outputs the systematic and recursive convolution sequences, while the other encoder outputs the recursive convolution sequence only after discarding the systematic sequence. [11]. A typical example where the turbo encoder and decoder are used is depicted in the figure below:

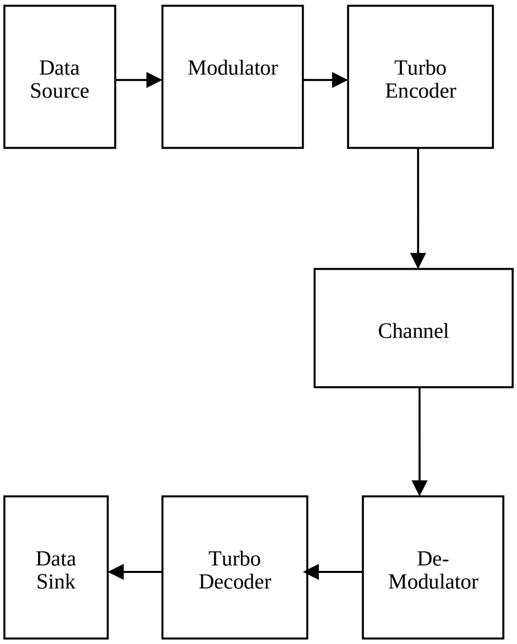

Fig.2 Use of Turbo Encoder and Decoder in Communication System

The turbo encoder is used after the modulator block and before the channel.
There are various schemes to implement the turbo encoding among which the most commonly used are:
1) Maxium Aposteriori Probability (MAP): In this technique, the core idea is to use the maximum-likelihood algorithm to find out the most probable information bit that was transmitted. The MAP technique tries to reduce the bit or symbol error probability.
2) Log-MAP: This avoids the approximations used in the Max-Log-Map algorithm by using a corrective function when a maximization operation is reached.
3) Max-Log-Map: This technique is a modification or derivative of the MAP algorithm wherein the computations are in the logarithmic domain. Hence it eases out the operations which are to be implemented.
4) Soft Output Viterbi Algorithm (SOVA): In this algorithm, an asymptotic version of the maximum likelihood algorithm is used for moderate and high SNR values. This approach finds the most probable information sequence within a transmitted code sequence. The different algorithms generally differ in the complexity of implementation which is estimated in terms of the following parameters v.i.z. additions, multiplications, max operations, look ups and exponentiation.
For a random channel, the turbo decoder is made up of the random variables x_k and y_k defined mathematically as:

$$x_k = (2d_k - 1) + i_k \qquad (6)$$
$$y_k = (2Y - 1) + q_k \qquad (7)$$

Here,
k is the time index
i_k and q_k are independent noises in the channel with noise variance σ^2

The turbo decoder is based closely on the encoding mechanism. It is depicted in the figure below.

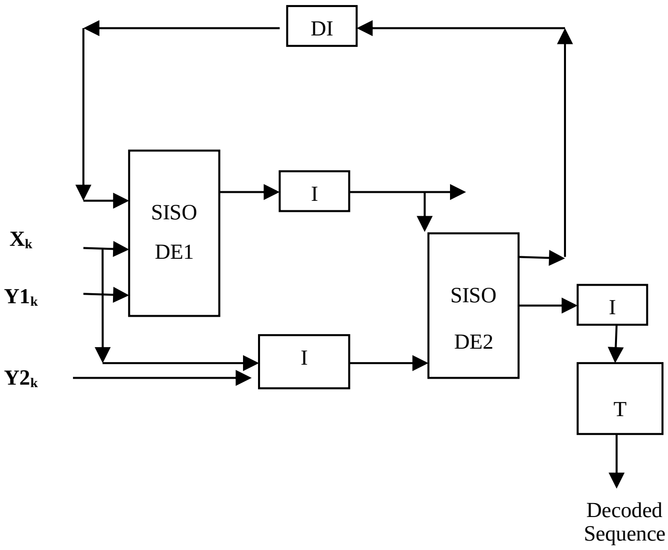

Fig. Structure of Turbo Decoder [11]

The different acronyms used in the above diagram are:
1) SISO: Soft Input Soft Output
2) I: Interleaver
3) DI: De-Interleaver
4) DE1: Decoder_1
5) DE_2: Decoder_2
6) T: Threshold or Decision Device

The above figure illustrates the iterative decoding procedure of by dint of Soft Input- Soft Output decoding mechanism. The SISO Decoder_1 is responsible for generating the soft output. Subsequently, the extrinsic information is produced. The second decoder uses the extrinsic information after interleaving. The second decoder then generates the extrinsic information with interleaving and in a feedback loop passes it on to the first decoder. There are several applications of turbo encoding such as:

1) Deep Space Communication
2) Digital Video Broadcast
3) W-CDMA etc.

The challenging aspect remains the decision to stop the iterative decoding process. It is given by:

II. PREVIOUS WORK

Yang et al. [1] put forth that the codes that were spatially connected and were like the turbo codes (SC-TCs) exhibited very good thresholds of decoding because of the saturation effect of decoding phenomenon. In the region of the waterfall and for average lengths of block, the simulation outcomes show very improved BER performance in the same region. The researchers mainly focus on the concept of spatial coupling and explore it in the context of turbo codes. They mainly study the impact of coupling on the SC-TCs performance on the ground that whether the spatial coupling can improve or contain the minimum turbo code distance. This led to the consideration of error floor outcome.

Chen et al. [2] discuss that Polar codes (PCs) have attracted significant attention in the last decade, especially after their adoption in the forthcoming 5G wireless networks. However, previous studies focused on coherent polar codes, which always rely on the strong assumption of available perfect channel state information. Instead, in this paper, authors investigate the use of PCs in noncoherent systems. First, a binary differential phase shift keying (BDPSK) demodulator is concatenated with a polar decoder to form the non-coherent detector, where successive cancellation (SC) is applied. The simulation results demonstrate that the SC-based PCs for noncoherent detection have approximately a discrepancy of only 3 dB compared with the coherent counterpart in noncoherent channels. Furthermore, in order to further decrease this discrepancy, they replace the BDPSK demodulator with a soft-input soft-output (SISO) multiple symbol differential sphere decoding demodulator. Similarly, the SC-based PC decoder is replaced by the SISO belief propagation-based PC decoder, and by using this novel architecture, an iterative noncoherent detector is constructed. Benefiting from further invoking extrinsic information transfer chart tool and the dynamic window-size detection scheme, the performance of the proposed iterative noncoherent detector becomes competitive with its coherent one in practical applications, since the performance degradation is reduced to 1 dB.

Moloudi et al. [3] introduce the concept of spatially coupled turbo-like codes (SC-TCs) as the spatial coupling of a number of turbo-like code ensembles. In particular, they consider the spatial coupling of parallel concatenated codes (PCCs), introduced by Berrou et al., and that of serially concatenated codes (SCCs), introduced by Benedetto et al.. Furthermore, they propose two extensions of braided convolutional codes (BCCs), a class of turbo-like codes which have an inherent spatially coupled structure, to higher coupling memories, and show that these yield improved belief propagation (BP) thresholds as compared to the original BCC ensemble. They derive the exact density evolution (DE) equations for SC-TCs and analyze their asymptotic behavior on the binary erasure channel. They also consider the construction of families of rate-compatible SC-TC ensembles. Their numerical results show that threshold saturation of the belief propagation (BP) decoding threshold to the maximum a-posteriori threshold of the underlying uncoupled ensembles occurs for large enough coupling memory. The improvement of the BP threshold is especially significant for SCCs and BCCs, whose uncoupled ensembles suffer from a poor BP threshold. For a wide range of code rates, SC-TCs show close-to-capacity performance as the coupling memory increases. They further give a proof of threshold saturation for SC-TC ensembles with identical component encoders. In particular, they show that the DE of SC-TC ensembles with identical component encoders can be properly rewritten as a scalar recursion. This allows us to define potential functions and prove threshold saturation using the proof technique recently introduced by Yedla et al.

Cai et al. [4] present the block Markov superposition transmission of BCH (BMST-BCH) codes, which can be constructed to obtain a very low error floor. To reduce the implementation complexity, they design a low complexity iterative sliding-window decoding algorithm, in which only binary and/or erasure messages are processed and exchanged between processing units. The error floor can be predicted by a genie-aided lower bound, while the waterfall performance can be analyzed by the density evolution method. To evaluate the error floor of the constructed BMST-BCH codes at a very low bit error rate (BER) region, they propose a fast simulation approach. Numerical results show that, at a target BER of 10−15, the hard-decision decoding of the BMST-BCH codes with overhead 25% can achieve a net coding gain (NCG) of 10.55 dB. Furthermore, the soft-decision decoding can yield an NCG of 10.74 dB. The construction of BMST-BCH codes is flexible to trade off latency against performance at all overheads of interest and may find applications in optical transport networks as an attractive candidate.

Liva et al. [5] explain the design of block codes for short information blocks (e.g., a thousand or less information bits) is an open research problem which is gaining relevance thanks to emerging applications in wireless communication networks. In this work, they review some of the most recent code constructions targeting the short block regime, and they compare them with both finite length performance bounds and classical error correction coding schemes. They will see how it is possible to effectively approach the theoretical bounds, with different performance vs. decoding complexity trade-offs.

Arıkan et al. [6] present that the “turbo revolution” of 1993 and the “rediscovery” of low-density parity-check (LDPC) codes shortly thereafter, the world of channel coding has undergone a major transformation. The “conventional wisdom” of the 1960s, 1970s, and 1980s was that, although capacity was theoretically achievable, practical constraints typically limited the performance of implementable code designs to fall several decibels short of capacity. This understanding was shattered with the invention of turbo codes, which achieved performance roughly 0.5 dB from capacity with moderately complex iterative BCJR decoding, and within just a few years, capacity approaching schemes using LDPC codes along with linear (in block length) complexity message passing decoding were becoming commonplace.

Boulat A. Bash et al. [7] Widely-deployed encryption-based security prevents unauthorized decoding, but does not ensure undetectability of communication. However, covert, or low probability of detection/ intercept (LPD/LPI) communication is crucial in many scenarios ranging from covert military operations and the organization of social unrest, to privacy protection for users of wireless networks. In addition, encrypted data or even just the transmission of a signal can arouse suspicion, and even the most theoretically robust encryption can often be defeated by a determined adversary using non-computational methods such as side channel analysis. Various covert communication techniques were developed to address these concerns, including Steganography for finite-alphabet noiseless applications and spread-spectrum systems for wireless communications. After reviewing these covert communication systems, this article discusses new results on the fundamental limits of their capabilities, as well as provides a vision for the future of such systems.

Babar et al. [8] discuss that the high detection complexity is the main impediment in future Gigabit-wireless systems. However, a quantum-based detector is capable of simultaneously detecting hundreds of user signals by virtue of its inherent parallel nature. This in turn requires near-capacity quantum error correction codes for protecting the constituent qubits of the quantum detector against the undesirable environmental decoherence. In this quest, they appropriately adapt the conventional non-binary Extrinsic Information Transfer (EXIT) charts for quantum turbo codes by exploiting the intrinsic quantum-to-classical isomorphism. The EXIT chart analysis not only allows us to dispense with the time-consuming Monte-Carlo simulations, but also facilitates the design of near-capacity codes without resorting to the analysis of their distance spectra.

They have demonstrated that their EXIT chart predictions are in line with the Monte-Carlo simulations results. They have also optimized the entanglement-assisted QTC using EXIT charts, which outperforms the existing distance spectra based QTCs. More explicitly, the performance of their optimized QTC is as close as 0.3 dB to the corresponding hashing bound.

Lentmaier et al. [9] investigated the impact of spatial coupling on the thresholds of turbo-like codes. Parallel concatenated and serially concatenated Convolutional codes as well as braided Convolutional codes (BCCs) are compared by means of an exact density evolution (DE) analysis for the binary erasure channel (BEC). They propose two extensions of the original BCC ensemble to improve its threshold and demonstrate that their BP thresholds approach the maximum-a-posteriori (MAP) threshold of the uncoupled ensemble. A comparison of the different ensembles shows that parallel concatenated ensembles can be outperformed by both serially concatenated and BCC ensembles, although they have the best BP thresholds in the uncoupled case.

Chen et al. [10] proposes a class of rate-compatible LDPC codes, called protograph-based Raptor-like (PBRL) codes. The construction is focused on binary codes for BI-AWGN channels. As with the Raptor codes, additional parity bits are produced by exclusive-OR operations on the precoded bits, providing extensive rate compatibility. Unlike Raptor codes, the structure of each additional parity bit in the protograph is explicitly designed through density evolution. The construction method provides low iterative decoding thresholds and the lifted codes result in excellent error rate performance for long-blocklength PBRL codes. For short-blocklength PBRL codes the protograph design and lifting must avoid undesired graphical structures such as trapping sets and absorbing sets while also seeking to minimize the density evolution threshold. Simulation results are shown in information block sizes of k = 192, 16368 and 16384. Comparing at the same information block size of k = 16368 bits, the PBRL codes outperform the best known standardized code, the AR4JA codes in the waterfall region. The PBRL codes also perform comparably to DVB-S2 codes even though the DVBS2 codes use LDPC codes with longer block lengths and are concatenated with outer BCH codes.

Table.1 Comparative Complexity Tabulation for Different Decoding Mechanisms [11]

	MAP	Log-Map	Max Log-Map	SOVA
Addition	$2.2^K.2^V$	$6.2^K.2^V$ +6	$4.2^K.2^V$ +8	$2^K.2^V$ +9
Multiplications	$5.2^K.2^V$ +8	$2^K.2^V$	$2.2^K.2^V$	$2^K.2^V$
Max. Operations		4.2^V-2	4.2^V-2	2.2^V--1
Look-ups		4.2^V-2		
Exponentiation	$2.2^K.2^V$			

The tabulation shows that different algorithms have different complexities and hence should be adopted accordingly. The complexities are estimated in terms of the various operations which need to be performed. The evaluation of any algorithm needs to consider the amount of operations which need to be performed. With an eye on the computational complexity, it can be seen that the SOVA algorithm is computationally less complex relatively and also attains good BER performance.

Conclusion:

It can be concluded from the previous theoretical discussions that turbo codes are extremely effective for their near Shannon limit of BER and SNR requirement. However, different variants of the decoding process pose different complexities and hence one needs to choose a technique as per the system requirements. This paper has presented latest trends in the domain with its salient feature. Finally a complexity analysis has also been presented for easy reference.

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