

Design and ASIC Implementation of a 3GPP LTE-Advance Turbo Encoder and Turbo Decoder

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Abstract- This paper presents the design and development of an efficient VLSI architecture for 3GPP advanced Turbo decoder by utilizing the convolutional interleaver. The high-throughput 3GPP Advance Turbo code requires turbo decoder architecture. Interleaver is known to be the main obstacle to the decoder implementation and introduces latency, due to the collisions it introduces in accesses to memory. In this paper, we propose a low-complexity Soft Input Soft Output (SISO) turbo decoder for memory architecture to enable the Turbo decoding that achieves minimum latency. Design trade-offs in terms of area and throughput efficiency are explored to find the optimal architecture. The proposed Turbo decoder has been modeled using Simulink; various test cases are used to estimate the performances. The results are analyzed and achieved 50% reduction in computation time along with reduced BER (e-3). The hardware of the Turbo Encoder and Turbo Decoder has been modeled in Verilog, simulated in Modelsim, synthesized using TSMC 65 nm Synopsys Design compiler and physical implementation has been carried out using IC Compiler.

Keywords: Convolutional interleaver, SOVA, Turbo decoder, MAP decoder, VLSI ASIC, 3GPP LTE.

I. INTRODUCTION

3GPP Long Term Evolution (LTE) [1], which is a set of enhancements to the 3G Universal Mobile Telecommunications System (UMTS) [2], has received tremendous attention recently and is considered to be a very promising 4G wireless technology. For example, Verizon Wireless has decided to deploy LTE in their next generation 4G evolution. One of the main advantages of 3GPP LTE is high throughput. For example, it provides a peak data rate of 326.4 Mbps for a 4x4 antenna system, and 172.8 Mbps for a 2x2 antenna system for every 20 MHz of spectrum. Furthermore, LTE-Advance [3], the further evolution of LTE, promises to provide up to 1 Gbps peak data rate. The channel coding scheme for LTE is Turbo coding [4]. The Turbo decoder is typically one of the major blocks in a LTE wireless receiver. Turbo decoders suffer from high decoding latency due to the iterative decoding process, the forward-backward recursion in the maximum a posteriori (MAP) decoding algorithm and the

interleaving/de-interleaving between iterations. Generally, the task of an interleaver is to permute the soft values generated by the MAP decoder and write them into random or pseudo-random positions.

II. FUNDAMENTALS OF TURBO CODES

In order to explain the proposed Turbo decoder architecture, the fundamentals of Turbo codes are briefly described in this section.

Turbo encoder structure

As shown in Fig. 1, the Turbo encoding scheme in the LTE standard is a parallel concatenated convolutional code with two 8-state constituent encoders and one convolutional interleaver [5]. The function of the convolutional interleaver is to take a block of N-bit data and produce a permutation of the input data block. From the coding theory perspective, the performance of a Turbo code depends critically on the interleaver structure [8]. The basic LTE Turbo coding rate is 1/3. It encodes an N-bit information data block in to a code word with 3N+12 data bits, where 12 tail bits are used for trellis termination. The initial value of the shift registers of the 8-state constituent encoders shall be all zeros when starting to encode the input information bits. LTE has defined 188 different block sizes. The convolutional encoder can be represented as follows [6]:

- $g0 = 1 + D + D2 + D3 + D6$
- $g1 = 1 + D2 + D3 + D5 + D6$

The convolutional encoder basically multiplies the generator Polynomials by the input bit string, as follows:

- $A(x) = g0(x) * I(x) = a b c \dots g$
- $B(x) = g1(x) * I(x) = P Q R \dots V$

Interleaving the two outputs from the convolutional encoder yields $E(x) = aPbQcR \dots gV$, which can also be written as:

$$E(x) = (a0 b0 c0 \dots g0) + (0P0Q0R \dots 0V) = A(x2) + x*B(x2)$$

Therefore, $E(x) = A(x2) + x*B(x2)$ and $A(x2) = g0(x2) + I(x2)$ and $B(x2) = g1(x2) * I(x2)$, with the following:

$$E(x) = g0(x2) * I(x2) + x * g1(x2) * I(x2) \\ = I(x2) * (g0(x2) + x * g1(x2))$$

$$= I(x2) * G(x)$$

Where $G(x) = g0(x2) + x * g1(x2)$

i.e. $G(x) = 1 + x + x^2 + x^4 + x^5 + x^6 + x^7 + x^{11} + x^{12} + x^{13}$.

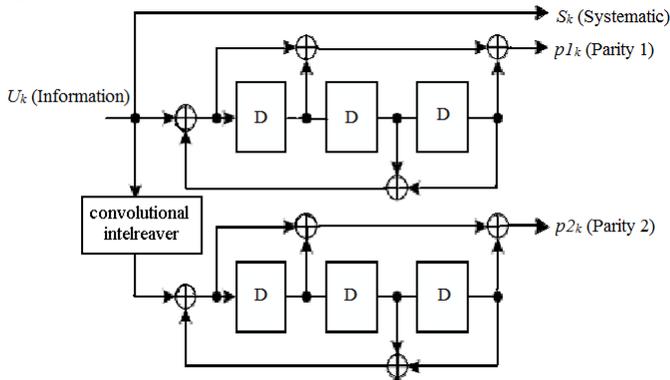


Fig 1: Structure of rate 1/3 Turbo encoder in LTE [7].

Turbo decoder structure

The basic structure of a Turbo decoder is functionally illustrated in Fig.2. A turbo decoder consists of two maximum a posteriori (MAP) decoders separated by an interleaver that permutes the input sequence. The decoding is an iterative process in which the so-called extrinsic information is exchanged between MAP decoders. Each Turbo iteration is divided in to two half iterations. During the first half iteration, MAP decoder 1 is enabled. It receives the soft channel information (soft value L_s for the systematic bit and soft value L_{p1} for the parity bit) and the a priori information L_a^1 from the other constituent MAP decoder through deinterleaving to generate the extrinsic information L_e^1 at its output. Likewise, during the second half iteration, MAP decoder 2 is enabled, and it receives the soft channel information (soft value L_s for a permuted version of the systematic bit and soft value L_{p2} for the parity bit) and the a priori information L_a^2 from MAP decoder1 through interleaving to generate the extrinsic information L_e^2 at its output. This iterative process repeats until the decoding has converged or the maximum number of iterations has been reached.

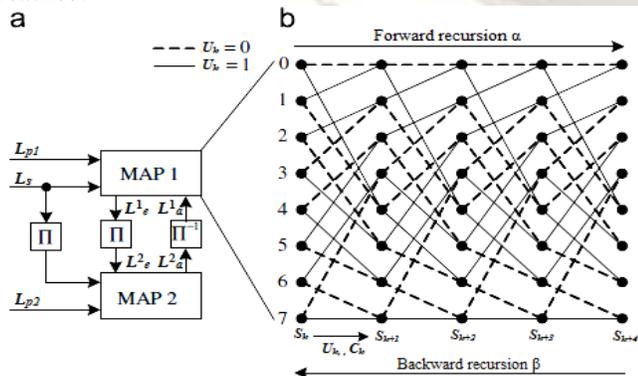


Fig.2: Basic structure of an iterative Turbo decoder [7].

(a)Iterative decoding based on MAP decoders.

(b) Forward/backward recursions on the trellis diagram.

Convolutional Interleaver

A convolutional interleaver [8] consists of N rows of shift registers, with different delay in each row. In general, each successive row has a delay which is J symbols duration higher than the previous row as shown in Fig. 3. The code word symbol from the encoder is fed into the array of shift registers, one code symbol to each row. With each new code word symbol the commutator switches to a new register and the new code symbol is shifted out to the channel. The i-th ($1 \leq i \leq N-1$) shift register has a length of (i-1)J stages where $J = M/N$ and the last row has M-1 numbers of delay elements. The convolutional deinterleaver performs the inverse operation of the interleaver and differs in structure of the arrangement of delay elements. Zeroth row of interleaver becomes the N-1 row in the deinterleaver. 1st row of the former becomes N-2 row of later and so on.

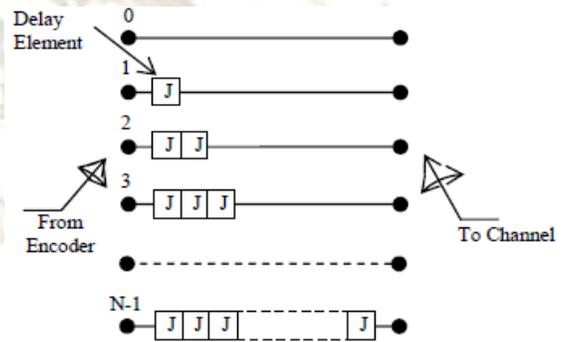


Fig 3: convolutional interleaver [8].

In order to verify the Verilog HDL models for the interleaver and deinterleaver the authors have developed another top level Verilog HDL model, combining interleaver and deinterleaver [8]. The scrambled code words from the output of the interleaver is applied as input to the deinterleaver block along with clock as synchronization signal. It is observed in Fig 4 that the scrambled code word is converted into its original form at the output of the deinterleaver block.

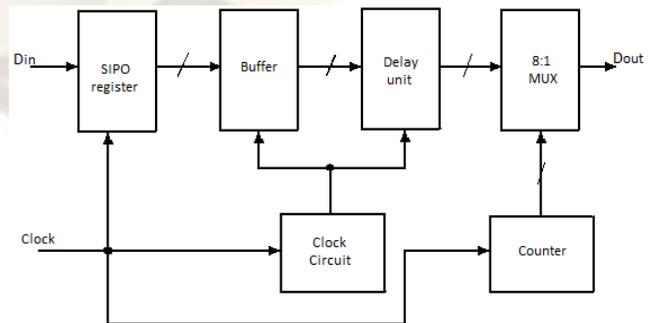


Fig 4: Block diagram of 8 bit convolutional interleaver [8].

III. SOFTWARE ANALYSIS OF TURBO DECODER

Simulink model of a Turbo Encoder and Turbo Decoder are shown below.

Turbo Encoder

It consists of two convolutional encoders. The outputs of the turbo encoder are the information sequence, together with the corresponding parity sequence produced by first encoder and the parity sequence produced by the second encoder block, the input to second encoder is through interleaver, which scrambles the data bit sequence. Simulation model of Turbo encoder –decoder is shown in Fig. 5

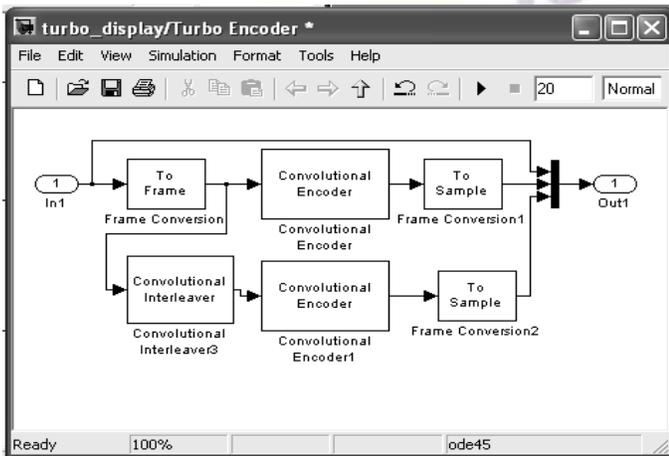


Fig 5: Simulink Model of Turbo Encoder

Turbo Decoder

The proposed Turbo decoder shown above in Fig 6 uses iterative decoding. The turbo code decoder is based on a modified Viterbi algorithm that incorporates reliability values to improve decoding performance. The turbo decoder consists of M-elementary decoders one for each encoder in turbo encoding part. Each elementary decoder uses the Soft Decision Viterbi Decoding to produce a soft decision for each received bit. After an iteration of the decoding process, every elementary decoder shares its soft decision output with the other M-1 elementary decoders.

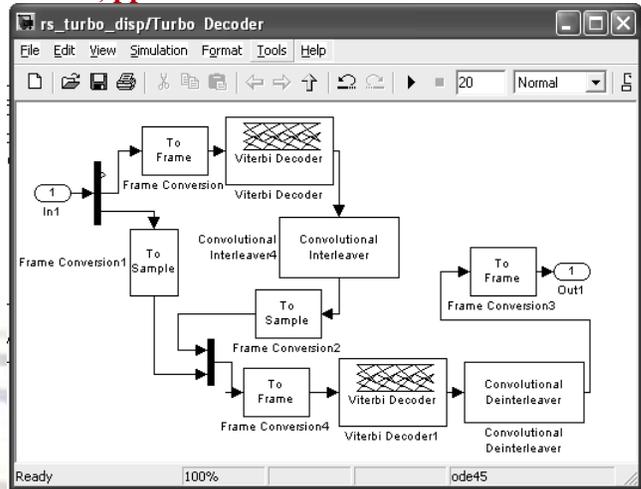


Fig 6: Simulink Model of Turbo Decoder

Channel

The AWGN Channel [1] block adds white Gaussian noise to a real or complex input signal. Each of the major blocks mentioned above have individual sub blocks which are configured to meet the Specifications (After scaling, keeping in mind the mathematical constraints of modeling a real time system).

IV. WORK FLOW

First Simulink model for turbo encoder and Turbo decoder is developed on MATLAB platform. The verilog HDL coding is made on Modelsim and verified. The HDL codes are synthesized by Synopsys Design Compiler, Finally the physical design [9] is implemented using IC Compiler. Fig 7 shows the work flow for implementation.

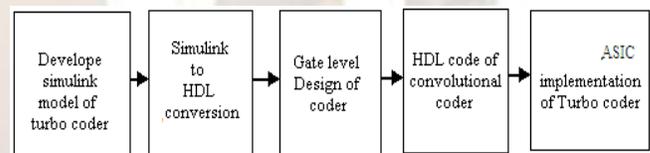


Fig 7: Work flow for implementation

V. RESULTS

Software Model

With the above Turbo encoder, Turbo decoder and channel specifications, the Bit Error Rate (BER) is analyzed for 3 samples per frame; it is 0.000254 so error rate is of order (10^{-3}) . The simulink model for turbo encoder and turbo decoder is as shown in Fig.5 and Fig 6. Similarly with the same encoder and decoder specifications are tested for different samples per frame. Here the computation time varies as the number of samples per frame increases; these cases also provide the BER of order 10^{-3} . The obtained results

are shown in the Table 1, and the obtained graph is as shown in Fig.8.

Bits Per frame	SNR(dB)	BER
3	5	0.254e-3
	10	0.214e-3
7	5	0.410e-3
	10	0.393e-3
12	5	0.324e-3
	10	0.311e-3
15	5	0.364e-3
	10	0.332e-3

Table1: Bits Per Frame Vs Signal to Noise Ratio & Corresponding BER

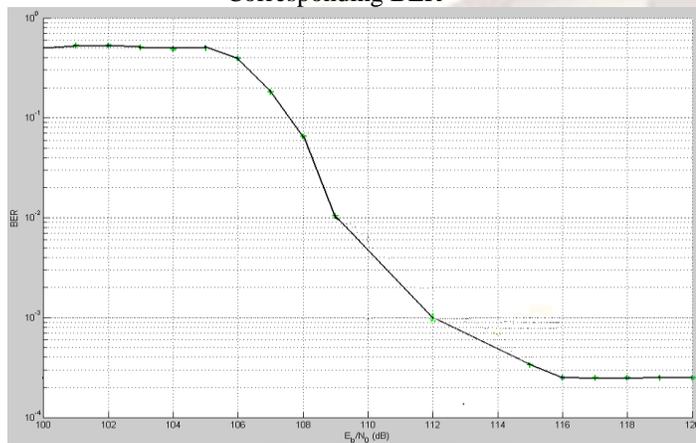


Fig 8: The Plot of BER along y-axis and signal to noise ratio (E_b/N_0) along x-axis.

Hardware Model

The final design after implementation of Turbo Encoder and Turbo Decoder is as shown in the Fig 9 (a) and (b).The standard cells placed in the core, pins and the routing of signals have been indicated for the advanced turbo decoder after ASIC implementation.

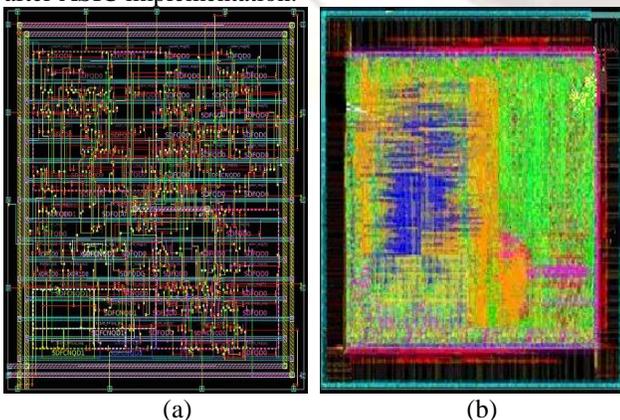


Fig 9: Physical design after implementation (a) Turbo Encoder (b) Turbo Decoder.

The physical design is carried out using IC Compiler tool for the Turbo Encoder and Decoder, and the obtained results have been discussed in this section. After placement, the power report of Turbo encoder as cell internal power is 149.8706 μ W (95%), net switching power of 7.4442 μ W (5%), dynamic power of 157.3148 μ W (100%) and cell leakage power of 95.6668 nW. The area is found to be combinational area of 169.20005 μ m², non combinational area of 448.2005 μ m², and total area of 617.40016 μ m²

.After placement, the power report of Turbo decoder is obtained, reported cell internal power is 268.52 mW (97%), net switching power of 8.5930 mW (3%), dynamic power of 277.12 mW (100%) and cell leakage power of 40.08 μ W. The area is found to be combinational area of 515.38 mm², non combinational area of 706.686 mm², and total area of 1222.071 mm².

VI. CONCLUSION

In this paper, presented a brief survey about turbo codes, designed a turbo encoder and turbo decoder on simulink and coded in Verilog HDL and carried an ASIC implementation of the same using IC Compiler TSMC 65 nm technology. The codes and coding techniques are carried by Viterbi decoder. For turbo codes, turbo decoders and their decoding algorithms like log-MAP/SOVA are used. Based on the algebraic constructions, the interleaver offers capability which enables Turbo decoding by using MAP decoders working concurrently. We proposed low complexity recursive architecture for generating the convolutional interleaver addresses on the fly. The convolution interleavers are designed to operate at full speed with the MAP decoders. The proposed architecture has been scaled and can be tailored for different throughput requirements.

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