Performance of Frame Oriented Turbo Codes on UMTS Channel with Various Termination Schemes

Arnaud GUEGUEN, Damien CASTELAIN

Mitsubishi Electric ITE
80 avenue des Buttes de Coësmes, Immeuble Germanium, 35700 Rennes, FRANCE
e-mail : {gueguen,castelain}@tcl.ite.mee.com

Abstract – This paper presents simulation results of frame oriented turbo codes [1] on simplified CDMA channel together with classical scheme of similar complexity, that is concatenation of convolutional code (K=9) with Reed Solomon code. Various trellis termination schemes are envisaged and in particular FOCTC (Frame Oriented Convolutional Turbo Code) which is a type of self-terminating scheme [2]. A new serial turbo decoding method of this latter scheme is presented as it performs better than the proposed parallel decoding scheme presented in [2] with equal complexity. At last, according to an analysis on AWGN channel, the importance of interleaver design is underlined.

I. Introduction

The third generation of mobile communication systems will offer different services, going from voice transmission to high rate packet data transmission. The latter service will work at a very low Bit Error Rate (BER) and requires therefore a powerful channel coding. Turbo codes [1] are known to be such very powerful codes achieving performance close to the Shannon bound on theoretical AWGN channel [3].

This paper argues through theoretical considerations and simulation results that burst oriented turbo codes (that is turbo codes with trellis termination) are also suitable in the realistic condition of UMTS channel. The first part describes the UMTS system model that was used, which is also the model that was defined for the decision process on channel coding for the standardisation of UMTS at ETSI (European Telecommunications Standards Institute). The second part reviews and evaluates the most common trellis termination schemes adapted to bursty transmission, with a particular interest for FOCTC (Frame Oriented Convolutional Turbo Codes [2]) which is a class of 'self-terminated' turbo code : a constraint on the internal interleaver guarantees that the single encoder returns to state zero at the end of each block, without transmitting any additional bit. The third part presents a new serial turbo decoding scheme for FOCTC, as opposed to the parallel decoding scheme proposed in [2]. Finally, the last part focuses on the design of the internal interleaver, the optimisation of which is crucial to reach low BER (down to 10^{-6}).

The results provided here were used by ETSI in the decision process of the coding scheme for UTRAN [4-7]

II. UMTS uplink model

The system model is a symbol based transmission chain for the uplink of UMTS (see figure 1). The data bits are encoded block by block with a Parallel Concatenated Convolutional Code (or turbo code, noted PCCC) with polynomials 13_{oct}, 15_{oct} and optimised interleaver as described in section VI. Channel block interleaving of length 10ms to 80ms is applied to the encoded block and 8 pilot bits are inserted at the beginning of each slot of length 0.625 ms. These pilot bits will be used at the reception side to perform the channel estimation. The binary stream is then modulated with QPSK modulation taking into account the Transmit Power Control (TPC) commands, and sent over the multipath mobile channel according to Lee's model [8]. White Gaussian noise is added with power spectral density N_0. At the reception side the searcher function is admittedly perfect so that the Rake receiver only performs maximum ratio path combining according to the channel estimation. It also generates the TPC command to transmit the next slot and generates a noise estimation that is used to normalise the soft values before entering the turbo decoder. The soft bits are deinterleaved (and the pilot bits are extracted) and passed in the turbo decoder. The elementary decoder uses a Log MAP algorithm [9] which consists in maximising the a posteriori probability of each decoded bit. 4 decoding iterations are used.

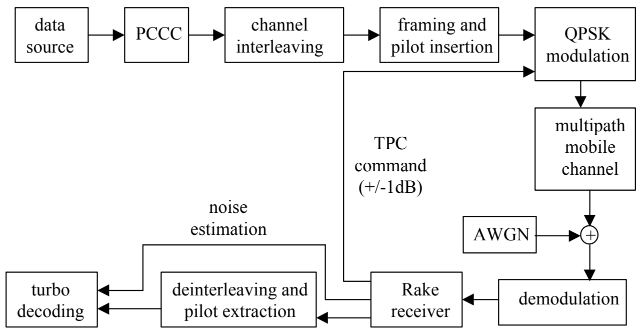

Figure 1 : UMTS symbol based simulation chain

III. Trellis termination of turbo codes

In a burst transmission it is suitable that the convolutional encoder returns to the zero state at the end of each coded block to 'protect' equally both ends of the block. In the case of PCCC the information sequence in encoded twice (yielding a basic rate of 1/3), first in its original order and then after interleaving, so that the termination has to apply to both trellises [10]. This is commonly achieved by various techniques :

- Catalytic Bit Processing (CBP) [11] :

This method consists in inserting known bits (for instance null bits) at known positions in the information block entering the turbo encoder. Before interleaving, i.e. at the input of the first elementary encoder, half of these bits are put at the end of the information block and half are randomly spread in the block, so that after interleaving, i.e. at the input of the second elementary encoder, the bits that were at the end are spread on the interleaved block and vice versa. The inserted systematic bits are punctured before transmission and reinserted at the decoding side with highest confidence value (highest LLR). Therefore, in the decoding process the metrics of the states corresponding to these bits are reinforced, providing thereby a higher protection to the neighbouring bits : according to the positions where the bits were inserted, the bits that benefit from this protection are found at the end and in some random places of the non interleaved and interleaved blocks. This method has several drawbacks : it does not make the encoders return to zero so that the end of the block is not protected exactly as the beginning. Besides it increases the overall complexity as the insertion and puncturing of the catalytic bits depend on the interleaver. At last it requires the transmission of additional bits which is detrimental in terms of E_b/N_0 for small blocks, where E_b is the energy per information bit. In the case of UMTS, it was proposed to insert 6 catalytic bits, leading to the transmission of 12 additional bits.

- Tail bits :

Each encoder is fed by its own output after encoding the information sequence : it returns to zero after flushing K-1 bits from its memory, where K is the constraint length of each elementary encoder (K=4 in the present case). One drawback is the E_b/N_0 penalty due to additional bits transmission (12 bits in the case of UMTS).

- FOCTC [2] :

This method uses only one encoder working twice as fast as in classical PCCC : the N data bits enter twice the same encoder, first in their original position and then in their interleaved position (see figure 2). If the interleaving law f satisfies f(i)-i = 0 mod L for all index i (where L is the period of the encoder defined in [2]) then the encoder returns to zero after encoding the 2N bits. The main interest of this method is that it does not require any additional bit transmission, which is especially interesting for small block sizes. Besides this scheme does not influence the puncturing law. One drawback is the further constraint on the interleaver when optimising it.

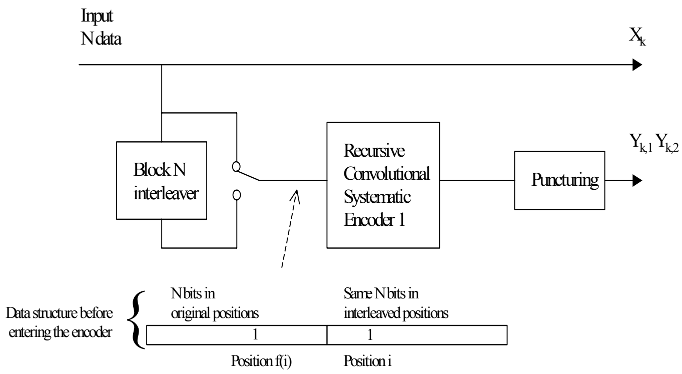

Figure 2 : FOCTC encoder

IV. Serial decoding of FOCTC

The method suggested in [2] to decode the FOCTC is to apply the decoding algorithm (Log MAP here) to the whole 2N soft bits sequence at each iteration, yielding two pieces of partial extrinsic information used by the next iteration (see figure 3).

This method corresponds to the so-called parallel turbo decoding method and it is likely to converge better than any other turbo decoding scheme, i.e. it should give the best performance when a huge number of iterations is performed, as explained in [12]. Indeed it respects the symmetry of the encoding process : at the input of each iteration, the non interleaved part and the interleaved part share the same amount of energy, as was the case at the output of the turbo encoder.

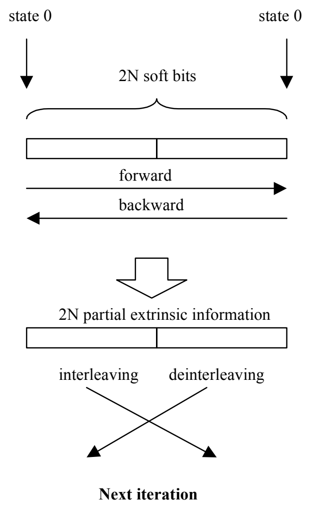

Figure 3 : one parallel decoding iteration of FOCTC as proposed in [2]

However, in a practical case, when few decoding iterations are used (4 here), this parallel scheme performs worse than the serial scheme that is described below (see figure 4), comparing decoding processes with similar complexity.

A serial decoding scheme for FOCTC is not straightforward because of the structure of the encoder. Indeed, unlike classical PCCC only one elementary encoder is used : the non interleaved part is concatenated to the interleaved part and the whole block enters the elementary encoder. Thus, at the receiver side, one is tempted to use only one elementary decoder working on the whole 2N bits sequence, and exploiting the trellis termination at the ends of the sequence. Unfortunately, as mentioned above, the resulting scheme is a parallel scheme. Consequently the proposed serial decoding method consists in splitting the 2N soft bits block - at the end of which the trellis is in the zero state- into 2 consecutive blocks of size N+D overlapping each other on D bits, and to apply the decoding algorithm to each of them separately, each half block producing extrinsic information used to decode the next one. The trellis is in the zero state at one end of each half block and in an unknown state at the other end, but the D overlapping bits enable to initialise correctly the decoding parameters for the N bits part, provided D is in the order of a few constraint lengths.

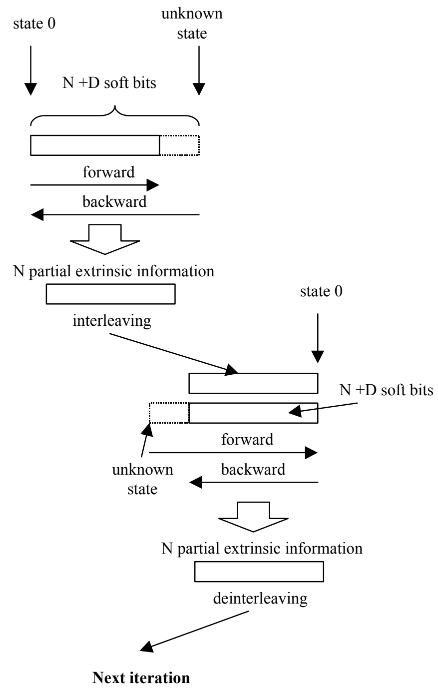

Figure 4 : one decoding iteration of the suggested serial decoding process for FOCTC

This serial scheme outperforms the parallel scheme with similar complexity at least for the first decoding iterations (see figure 5) because the extrinsic information produced by each half block is used by the next one as soon as it is available. However this scheme may perform a bit worse than the parallel scheme when many iterations are used because it does not respect the symmetry between the non interleaved part and the interleaved part that exists at the output of the encoder. Nevertheless, this last behaviour was not observed in simulations reported on figure 5.

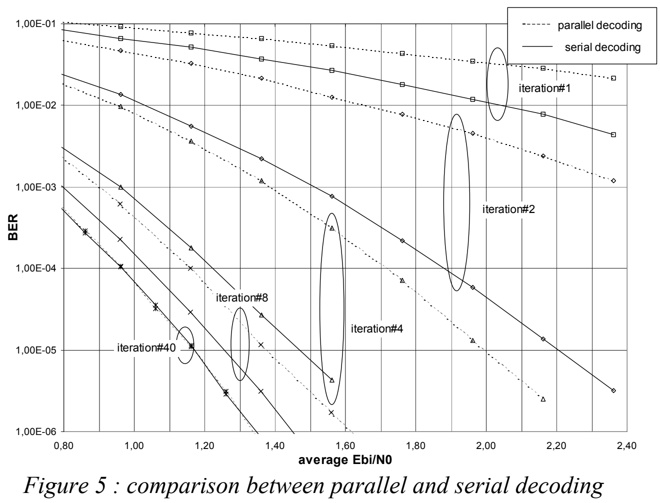

Figure 5 : comparison between parallel and serial decoding of FOCTC (the complexity of one iteration of each scheme is approximately the same)

V. Some simulation results

Figures 6 and 7 show some simulation results of turbo codes with the three different trellis terminations. They also provide results of a classical scheme (convolutional code K=9 with Reed Solomon as external code) simulated in the same conditions and known to have similar complexity [13].

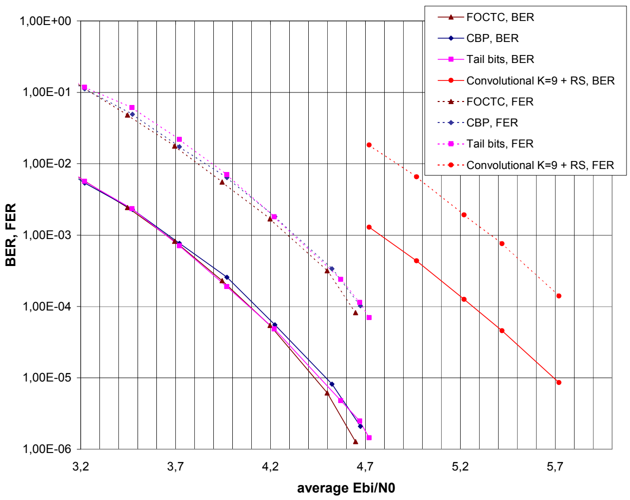

Figure 6 : simulation results of burst oriented turbo codes on simplified UMTS uplink channel with the various trellis terminations (N=640,speed=30km/h,channel interleaver length=10ms, rate=1/3,4 decoding iterations)

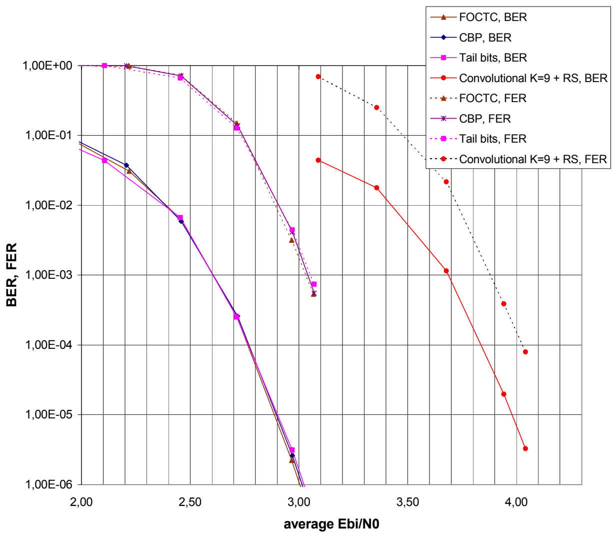

Figure 7 : simulation results of burst oriented turbo codes on simplified UMTS uplink channel with the various trellis terminations (N=5120,speed=3km/h,channel interleaver length=80ms, rate=1/3,4 decoding iterations)

The various termination schemes perform similarly but FOCTC may be preferable for small block sizes because no additional bits are transmitted.

Turbo codes outperform the classical scheme of equivalent complexity by at least 1.1dB in terms of BER and 0.9dB in terms of FER. Besides, by using CRC as a stop criterion in the iterative process [14], the maximum number of iterations can be increased while keeping the average complexity to a constant value, thus achieving an important peformance gain with no complexity increase.

VI. Interleaver design

On AWGN channel, simulations show that turbo decoding converges very close to the ML (Maximum Likelihood) decoding error bound in terms of BER and at high SNR (see figure 8). This error bound is given in [15] by :

$$P_b\left(\frac{E_b}{N_0}\right) \approx \frac{1}{2}\sum_m D_m \operatorname{erfc}\left(\sqrt{m\frac{R_c E_b}{N_0}}\right) \qquad (1)$$

where the coefficients D_m are derived from the weight distribution of the code and R_c is the code rate. In [15] these coefficients are evaluated considering an average interleaver. In the present case, the first terms are measured by an exhaustive search so that the bound reflects the performance of one particular interleaver. Thus, the poorer the distance spectrum of a given turbo code, the higher the corresponding error bound and the sooner the error floor will appear. On figure 8, two interleavers are studied. Interleaver#1 is optimised and interleaver#2 is a random one. The partial distance spectrum of each interleaver is shown (D_m coefficients), and the derived analytical ML decoding error bound is drawn together with simulation results on AWGN channel.

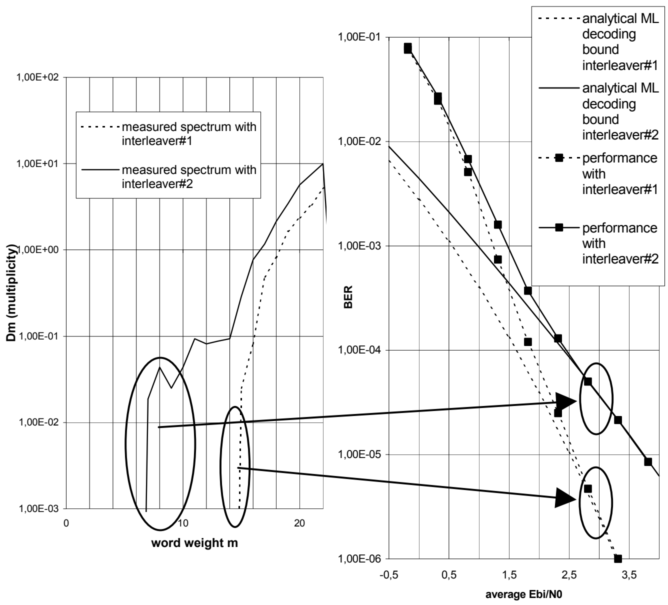

Figure 8 : influence of the distance spectrum on the error bound and on the performance of a turbo code on AWGN channel for 4 states PCCC, $(7,5)_{oct}$, N=320

It is clear that the optimisation of the internal interleaver will deeply influence the occurence of the error floor in the case of AWGN channel. This consideration can also be extrapolated to the realistic case of CDMA channel, all the more so as power control makes the channel close to the AWGN channel. As a consequence, an interleaver yielding a poor distance spectrum with a small minimum distance will also perform poorly on the UMTS channel as the error floor will show up early. This statement is illustrated on figure 9, where the same interleavers as in figure 8 were used.

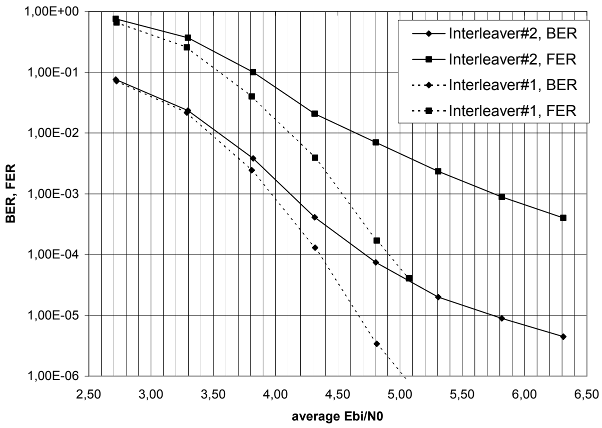

Figure 9 : influence of interleaver design on the performance on UMTS channel (N=320,speed=3km/h,channel interleaver length=10ms, rate=1/3, 20 decoding iterations)
interleaver#1 : optimised (good minimum distance)
interleaver#2 : random interleaver (poor distance spectrum)

Designing interleavers with good spectrum, i.e. in particular with high minimum distance, is also crucial in the case of realistic channel. Moreover, as mentioned in [16], it is also important to take into account the iterative aspect of turbo decoding when designing the interleaver, that is to minimize the correlation propagation of extrinsic information.

VII. Conclusion

Simulations over a realistic UMTS channel model show that frame oriented turbo codes are well suited for packet data transmission on radio links as they outperform classical schemes with similar complexity. Besides all termination schemes are equivalent in terms of performance as soon as the block size is a few hundreds of bits, but some schemes such as FOCTC may be preferable because their encoding process is more straightforward. A serial turbo decoding scheme is proposed for FOCTC, which performs better than the previously proposed parallel scheme with equal complexity. At last, the relationship between non optimised interleaver, poor distance spectrum and the so-called error floor occurence is pointed out on AWGN channel as well as on the considered UMTS channel.

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