Performance Evaluation of HARQ Technique with UMTS Turbo Code

Srđan S. Brkić and Predrag N. Ivaniš, *Member, IEEE*

Abstract - **The hybrid automatic repeat request technique (HARQ) represents the error control principle which combines an error correcting code and automatic repeat request procedure (ARQ), within the same transmission system. In this paper, using Monte Carlo simulation process, the characteristics of HARQ technique are determined, for the case of the Universal Mobile Telecommunication System (UMTS) turbo code.**

Keywords **— Automatic repeat request (ARQ), Hybrid automatic repeat request (HARQ), Monte Carlo simulation, UMTS Turbo code**.

I. Introduction

TURBO codes represent a specific class of linear block codes, used for *forward error correction* (FEC). Their invention has led to enormous progress in the error control theory and enabled realization of transmission systems with performances close to the Shannon limit [1]. Turbo encoder refers to a parallel concatenation of convolutional encoders and interleaver blocks. It has been shown that the best turbo codes are composed of *recursive systematic convolutional* (RSC) codes and pseudo-random interleavers [2].

The structure of the turbo encoder which has been applied in *Universal Mobile Telecommunication System* (UMTS) standard is presented in Fig. 1. The encoder has three output sequences: information sequence ($\boldsymbol{c_0}$), parity bits sequence produced by the first component RSC encoder ($\boldsymbol{c_1}$), parity bits sequence formed by coding permuted information sequence in the second RSC encoder ($\boldsymbol{c_2}$). The UMTS interleaver formats the input sequence in a predefined matrix and then permutes matrix elements using a pseudo-random algorithm defined in UMTS standard [3]. Reordered bits are afterwards sent to an interleaver output and coded in the second RSC encoder. Turbo code decoding process consists of many identical stages and requires the existence of two independent component decoders. In every decoding iteration, decoders exchange messages with soft decisions information. It is common to apply a *maximum a posteriori probability* (MAP) algorithm in component decoders, and then decoder's output can be expressed by *log-likelihood ratio* (LLR) as in [4]

$$LLR(i_k) = L_{sys} + L_{in} + L_{ext}\,, \tag{1}$$

S. S. Brkić is with the Inovation Center, Faculty of Electrical Engineering, University of Belgrade (e-mail: brka05@gmail.com).

P. N. Ivaniš is with the Faculty of Electrical Engineering, University of Belgrade (e-mail: predrag.ivanis@etf.rs).

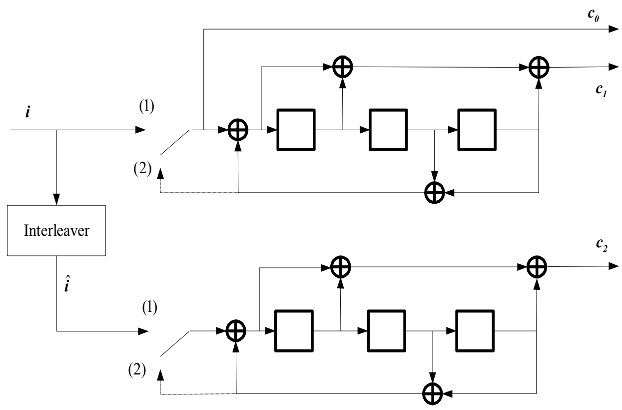

Fig. 1. UMTS turbo encoder structure.

where L_{sys} is the contribution of the systematic bit at discrete time i_k, L_{ext} is the contribution of all other systematic bits except for the one at time i_k, and all parity bits of one encoder. Parameter L_{in} is the information available by the other MAP decoder that represents the contribution of all systematic bits except for the one at time k and all parity bits of the other encoder. Parameter L_{ext}, called *extrinsic information*, is forwarded to the other decoder, where it is used as L_{in}, which leads to iterative cycles. Every iteration consists of two decoding stages, corresponding to individual MAP decoding processes [2].

Reliable transmission can also be achieved in other way, using ARQ procedures. This error control technique implies packet communication and the insertion of a small number of redundant bits in every packet, which helps to determine possible packet damage. *Cyclic redundancy check* (CRC) is usually used for this purpose, since it has a good error detecting ability and low complexity level [5]. If a receiver determines, using CRC check, that all bits are not transmitted correctly, the transmitter is informed by a feedback channel to perform the retransmission of damaged packet [6].

Hybrid ARQ procedures combine a classic ARQ principle with a FEC code. In this realization the packet (with an added CRC supplement) is coded using FEC code capable of correcting error patterns that appear most frequently. If an error pattern cannot be corrected, retransmission is needed. HARQ technique has a higher reliability than FEC system and can enable a greater throughput than classic ARQ technique.

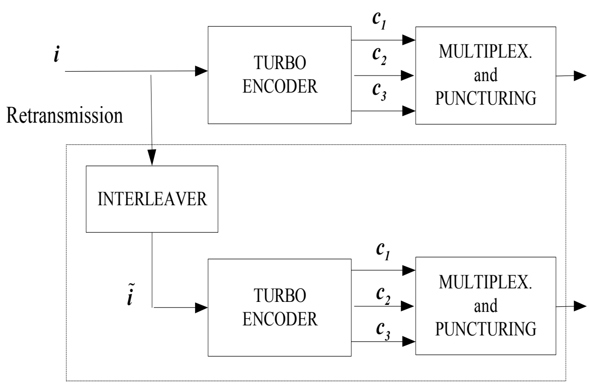

Fig. 2. Turbo ARQ encoder structure.

II. TURBO ARQ PROCEDURE

In this paper we apply a HARQ technique, presented in [7], where FEC subsystem uses UMTS turbo code. When a turbo decoder cannot correct all errors, the LLR values are stored to be used as a priori probabilities during the retransmission. When compared to turbo code principle, in turbo ARQ procedure realization it is necessary to implement a modification regarding the retransmission of damaged packets. The encoder structure, shown in Fig. 2, represents the modified version of classic turbo encoder. During the first transmission, the packet is coded using a standard turbo encoder. If a receiver indicates the need for retransmission, the transmitter of the packet permutes information message using a pseudo-random interleaver. Then, a new message is coded using an identical encoder, but the HARQ pseudo random interleaver is different from the one used within turbo encoder. During every additional retransmission a different pseudo-random pattern is used in the HARQ interleaver.

HARQ decoder structure, presented in Fig. 3, is similar to a classic turbo decoder. When an error pattern that cannot be corrected occurs, negative acknowledgment is sent and LLR values of each information bit are stored. When the replica of the packet is received, stored LLR values are used as a priori information during the decoding of the packet. During the first transmission, it is considered that a priori probabilities of information bits are $P(i_k=0) = P(i_k=1) = 0.5$. Then, the value of parameter $L_{in}(i_k)$ from eq. (1) is equal to 0. In the case of retransmission, the a priori probabilities of input symbols are not considered equal and $L_{in}(i_k)$ is set to $L'(i_k)$, the value of LLR from a previous transmission. Thus, new extrinsic information can be set to value $L_{ext}(i_k) + L'(i_k)$ and forwarded to the second component decoder. This can be done as a priori information was generated from a previous transmission and it is uncorrelated with the extrinsic information generated by the decoders themselves. In a similar fashion, $L'(i_k)$ can be used in the next iterations of decoding algorithm. Thus, the output of MAP decoders can be rewritten as

$$LLR(i_k) = L_{sys} + L_{in} + L_{ext} + L'(i_k)\,. \qquad (2)$$

As the turbo code used in every transmission has the same coding rate, it can be concluded that the combining of the received packets lowers the original code rate.

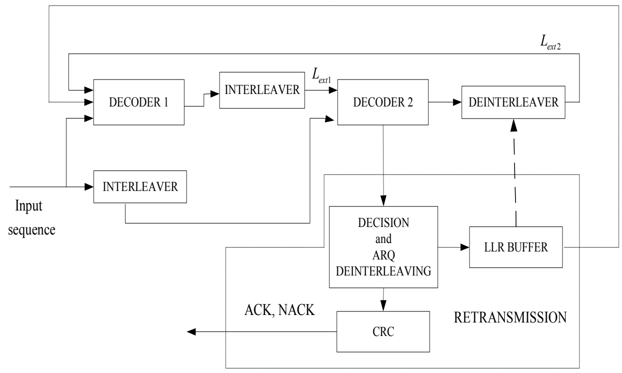

Fig. 3. Turbo ARQ decoder structure.

Thus, if a turbo code with rate 1/2 is used, after the first retransmission the rate of equivalent code has a lower value 1/4. The described packet combining algorithm is not the optimal one, but has a great advantage in terms of decoder complexity. All what is needed to do further is to reserve a memory location for LLR values and to realize the CRC subsystem.

III. SIMULATION ANALYSIS

The performances of the system that applies a turbo coding principle are commonly evaluated using a simulation procedure. In this paper, using Monte Carlo simulation method, the bit error rate (BER) performances of the presented HARQ procedure are determined as a function of energy per bit to noise power spectral density ratio (E_b/N_0) [8]. It is assumed that at the input of the receiver, along with the useful transmitted signal, additive white Gaussian noise (AWGN) exists. The bandwidth is chosen according to the Nyquist criterion, thus the intersymbol interference effect can be neglected.

In order to determine the improvement obtained using ARQ procedure, we performed analysis of the system without using the retransmission principle – a standard turbo forward error correction system according to UMTS standard. Before a code word is sent to a receiver, it passes through the puncturing block. Its task is to increase a coding ratio by deleting one parity check bit in every code word. Thus, a new code word contains one information bit and one control bit (R = 1/2) chosen according to the previous bit selection - if the previously chosen parity check bit belongs to the first RSC, then the second RSC control bit is selected and vice versa.

The turbo decoder uses an iterative decoding algorithm based on the MAP principle described in the first section. This algorithm is heuristic and there is no exact formula that gives a number of decoding cycles, necessary to achieve a stationary state. In general, the number of iterations depends on the code rate, interleaver structure and the codeword length. The influence of the number of iterations on the UMTS code bit error rate is shown in Fig. 4.

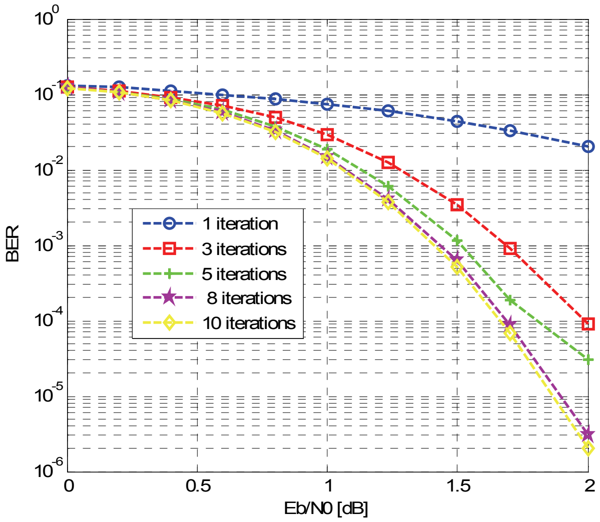

Fig. 4 The BER performances of 1/2 ratio turbo code for different numbers of decoding iterations.

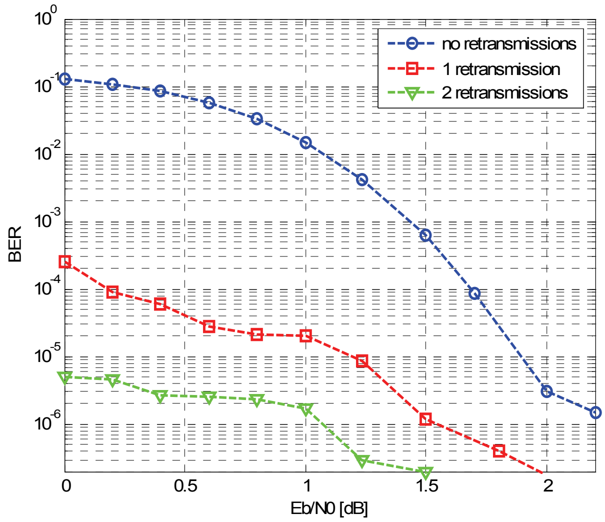

Fig. 5. The HARQ procedure performance – different numbers of retransmission impact.

The simulation analysis is performed on the information block length of 640 bits, formed from 637 information bits and 3 tail bits which are added to the end the first RSC trellis in all-zero state. The number of tail bits is equal to the encoder memory order. As a random interleaver is used, it is not possible to terminate the second RSC in all-zero state without additional bits.

It is obvious that increasing the turbo coding system performances rapidly improves with the number of decoding cycles. Thus, for example, the BER value of 10^{-4} can be achieved with E_b/N_0=2dB using 3 decoding iterations, while for the same error level it is required only E_b/N_0=1.65 dB with 8 decoding iterations. The simulation has shown that the sufficient number of iterations is I=8 for decoding of 640-bit block, and the further increase of decoding cycles does not lead to significant error correcting improvements. On the other hand, it may have a negative effect on delay-limited systems. In the further analysis of HARQ procedure it will be assumed that the values of transmitted bits are estimated after 8 decoding iterations.

In the simulation of HARQ technique we assumed that for each received packet a negative or affirmative acknowledgment was sent to a transmitter by a feedback channel. A small value of round trip time is chosen, that does not have a significant impact on system performances. A 16-bit CRC code with generator polynomial $x^{16}+ x^{15}+ x^2+1$ was used for error detection. CRC supplement was added to an information sequence to form a 640 bits long block which was coded by a punctured UMTS turbo encoder. When a turbo decoder had not corrected all errors, the information sequence was permuted before retransmission. A pseudo-random interleaver pattern was used, that was generated using the following recursion

$$X_{n+1} = (aX_n + c) \bmod N \,, \qquad (3)$$

where N is the block length, a and c are parameters, such that a–1 is a multiple of all prime factors of N and c is relatively prime to N and a–1 divisible by 4 if N is divisible by 4 [7].

Every time when a new interleaving pattern was required, different values of a and c were used. In the case when the information sequence had not been decoded correctly within the predefined number of transmissions, the next packet was transmitted. The corresponding performances of the HARQ system are presented in Fig. 5, when one or two retransmissions are used. A large number of retransmissions is not suitable, when delay due to decoding computation has a relatively high value.

The improvement brought by HARQ procedure is quite noticeable in the region with a low E_b/N_0 ratio. The system without retransmissions corresponds to the standard FEC turbo coding principle and BER≈ 10^{-1} can be achieved for E_b/N_0=0dB. On the other hand, by using HARQ techniques, BER≈ $2\cdot10^{-4}$ can be obtained in case of one retransmission and BER≈ $6\cdot10^{-6}$ can be obtained if two replicas of damaged packets are allowed. The reason for HARQ technique superiority is the effective packet combining algorithm that corresponds to the use of a lower rate code. But, the retransmission gain decreases with the increase of E_b/N_0 value. A BER curve that corresponds to turbo FEC system has an exponential dependence on E_b/N_0, while HARQ performance curves are approximately linearly dependent. For the greater values of $E_b/N_{0,}$ retransmissions become less frequent and their impact on the system performances is reduced. Thus, for E_b/N_0=2.2 dB and one retransmission the allowed bit error rate has value BER≈ $2\cdot10^{-7}$, which is relatively close to FEC system performances (BER≈ 10^{-6}). A BER level of the system with two retransmissions and the same E_b/N_0 ratio, is lower than 10^{-7}, but a further increase of E_b/N_0 ratio results in reducing the performance difference between systems with and without retransmissions.

The simulation that aims to examine the improvement that the presented HARQ techniques brings compared to the standard ARQ procedure, which does not use the packet combining algorithm, was also performed and the results are presented in Fig. 6. The number of retransmissions is limited to two.

The classical ARQ procedure is based on the assumption that the channel state changed between two transmissions and when a replica is transmitted the noise has a lower power level. Since in the channel only statistically independent AGWN exists, simple retransmission of damaged packets does not achieve any improvement and the ARQ system has the same performances as the turbo FEC system without the retransmission principle.

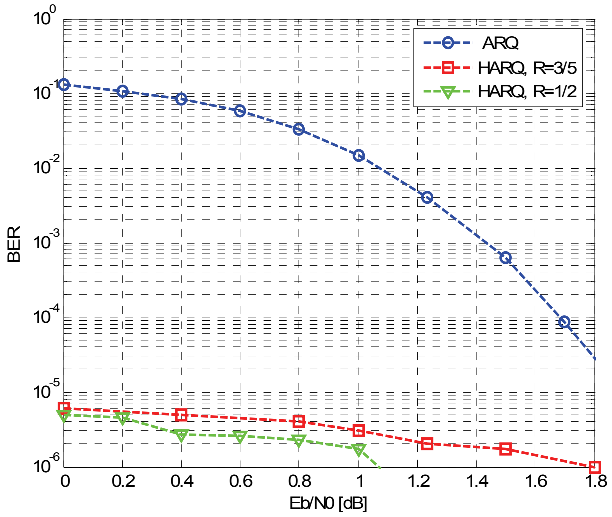

Fig. 6. BER comparison of HARQ and ARQ procedures.

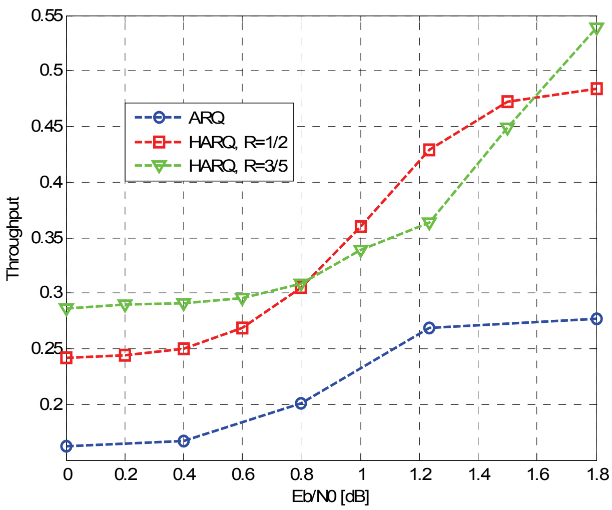

Fig. 7. Throughput comparison of HARQ and ARQ procedures.

The BER curve for the HARQ system with a turbo code with a higher coding ratio (R=3/5) is also shown in Fig. 6. The achieved performances are slightly worse, as expected. But, the advantage of using a turbo code with a higher ratio can be seen by analyzing the value of another important parameter - throughput. The throughput is defined as the ratio of the average number of bits accepted as error-free by the receiver to the total number of transmitted bits. The throughput values obtained for codes of interest are presented in Fig. 7. The additional puncturing of turbo code lowers its error correcting capabilities, but less parity check bits are sent to receiver. In the E_b/N_0 intervals where lower code protection does not increase the number of retransmission, this HARQ procedure enables higher throughput values. The differences are especially noticeable in the region with high E_b/N_0 values, then the throughput is close to its maximal value limited by the code rate. For example, at E_b/N_0=1.8dB the throughput obtained using the HARQ procedure with a higher code rate is approximately 0.54, and it is significantly higher than the value achieved using a procedure that implements 1/2 ratio turbo code. From the presented analysis it is clear that the code ratio can be chosen as a compromise of required error correcting capabilities and the desired throughput.

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