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Improved LTE turbo codes for NR

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1 Introduction

A Study on New Radio Access Technology was approved in RAN#71 meeting [1]. The channel coding scheme is a fundamental component for fulfilling the different requirements of next generation radio access technologies [2]-[4]. The current LTE coding schemes have not been designed for the new requirements of the identified usage scenarios such as eMBB (enhanced mobile broadband), mMTC (massive machine type communication), and uRLLC (ultra-reliable low latency communication).

In this contribution, we analyze the strengths and weaknesses of the existing LTE channel coding schemes in relation to the requirements of the new radio interface and we propose a new design of turbo codes that can compensate for the weaknesses of the legacy LTE turbo codes.

2 Analysis of the channel coding requirements the New Radio Access Technology

Each identified usage scenario has specific requirements related to the channel coding scheme:

- **eMBB**: for this usage scenario, the channel coding scheme should support a large range of data rates, from very low data rates for instant messages or control signaling to very high data rates (20 Gbps for downlink and 10 Gbps for uplink) [3] with improved error correction capabilities and at the price of a reasonable implementation cost. The coding scheme should be flexible in terms of data block sizes and coding rates. The different latency requirements for data and control planes should also be satisfied.
- **mMTC**: the use cases involving a massive distribution of sensors and actuators require the channel coding scheme to support small packets (a few dozen to hundred bits), with energy-efficient encoding and decoding which is necessary for mMTC long-life devices.
- **uRLLC**: the channel coding scheme must fulfil high reliability on small packets with very low latency.

3 Analysis of LTE turbo coding scheme

The LTE turbo code presents benefits inherent to the turbo code family:

- High **flexibility** with respect to data block length and coding rate: a unique code structure can be used for a large range of data block sizes and coding rates. The different coding rates are obtained by puncturing some transmitted data, allowing rate compatibility and incremental redundancy.
- Very good **error correction performance** at high to medium error rates for a large range of block sizes and coding rates: turbo codes keep very good performance when punctured. It has been

repeatedly observed that turbo codes tend to outperform LDPC codes at shorter block lengths and low coding rates. A recent study of channel coding for space mission telecommand links [5] has shown that coding schemes based on turbo codes can outperform the latest ones based on LDPC codes, especially for short to medium frame sizes.

- **Implementation maturity** and short time-to-market: turbo code implementation is mature and widely used. Continuing to use turbo codes would reduce the design time of the channel coding component. Combined with the very mature turbo decoder implementation, the time-to-market for the new radio interface would be reduced.

Observation 1: Turbo codes show native flexibility in code rates and frame sizes with a high implementation maturity.

Observation 2: Turbo codes can offer similar and often better performance than LDPC codes especially for short frame sizes.

On the other hand, the LTE turbo code presents some shortcomings that should be addressed in the new radio interface:

- **Error floor**: a known issue of the LTE TC is its poor performance at low error rates when transmitting data with coding rates higher than 1/3. This is due to the fact that, for some combinations of block size and coding rate, the LTE rate matching module leads to bad interactions between puncturing and interleaving in the turbo encoder structure, entailing early error floors in the error rate curve [6]. This shortcoming can be eliminated by **jointly designing and optimizing** the turbo code interleaver and the puncturing mechanism in order to avoid these negative interactions.
- **Trellis termination**: tail bits are used to terminate the trellis of the component convolutional codes of the LTE turbo code. Firstly, this results in a non-negligible bandwidth efficiency reduction for short frames. Secondly, this type of trellis termination introduces low-weight truncated codewords and does not ensure the same protection for all data bits, since tail bits are not encoded twice (i.e., turbo encoded) as regular data are, thus contributing to the error floor issue. A more efficient termination technique is the tail-biting technique [7]. This technique, already applied to the convolutional code used for the downlink channels of Narrow-Band IoT systems in Release 13. Last but not least, circular trellises make it easier for the implementation of parallel turbo decoding using several component decoders.

Observation 3: LTE turbo codes are far from achieving the full potential of turbo codes mainly due to the error floor and trellis termination issues.

Concerning **power consumption** and **hardware complexity**, turbo decoders are sometimes considered inferior to other decoder families (e.g. LDPC). However, most evaluations do not compare implementations supporting the same numbers of code rates and block lengths. The particular code rate values are also of great importance. Indeed, LDPC codes are more efficient at very high code rates, whereas turbo codes are best at low to medium code rates [7]. Complexity assessment greatly depends on the values of the coding rates and the number of possible combinations to implement. Meaningful efficiency metrics are needed to quantify the implementation complexity of a receiver. Most of the current established efficiency metrics are based on counting operations, thus neglecting important issues like data and storage complexity and access [7].

Regarding **high throughput turbo decoders**, several implementations providing useful data throughput beyond 1 Gbps were reported in the literature: for instance, [8] and [9] report VLSI implementations of

turbo decoders achieving processing throughputs of respectively 1.28 Gbps and 2.15 Gbps, when decoding the longest frames (6144 bits) supported by LTE. A more recent paper [10] shows that fully parallel implementations of the LTE turbo decoder allow processing throughputs greater than 20 Gbps to be achieved with a TSMC 65-nm low-power technology.

Observation 4: State-of-the-art comparisons between codes are inaccurate in most cases since they are limited to computational complexity. Memory requirements and number of memory accesses are important parameters to be further considered.

Observation 5: The number of supported code rate / frame size combinations has a large impact on the complexity of some family of codes such as LDPC codes.

Observation 6: Very high throughput (>20Gbps) turbo decoder implementations are being proposed in the literature.

4 Performance of tail-biting turbo codes with jointly optimized interleaving parameters and puncturing patterns

The error performance curves presented in this section have been obtained with regular binary puncturing patterns of length Q ($Q \leq 16$) and an Almost Regular Permutation (ARP) interleaver, already adopted in several standards [11][12].

The interleaving function is given by the following equation:

$$\Pi(i) = \left(Pi + S(i \bmod Q)\right) \bmod K$$

where i denotes the address of the data symbol after interleaving and $\Pi(i)$ represents its corresponding address before interleaving. P is a positive integer relatively prime to K, K being the block length and the interleaver size. **S** is a vector containing Q integer values. The values of parameters P and $S(i), i = 0 \cdots Q-1$, are chosen to support the different block sizes and coding rates.

It was shown in [13] that the QPP interleavers of the LTE turbo code can be seen as a particular case of ARP interleavers, in which the values of the periodic shifts follow the quadratic term of the QPP interleaver function.

Figure 1, Figure 2 and Figure 3 show the performance comparison of the LTE turbo code with a new designed turbo code including tail-biting termination and joint optimization of the interleaver and puncturing pattern, for 3 different LTE block sizes and various coding rates, in AWGN channel.

Figure 4 and 5 show the performance of the improved turbo code for two new block sizes (K = 100 and 8000) and coding rates 1/5 and 8/9 (extreme frame sizes and code rate values).

In these figures, the obtained error rate performance for the improved TC is given as an example and can be subject to further improvement. The introduced modifications to the existing LTE TC for coding rates higher than 1/3 are minimal since they are limited to the trellis termination, puncturing and interleaving. These modifications have negligible (almost inexistent) impact on hardware complexity. For coding rates lower than 1/3 (e.g. 1/5), each component convolutional code provides two parity bits instead of one.

The figures show that BLock Error Rates (BLER) down to 10^{-6} or lower can be achieved without significant change of the curve slope in all the simulated cases. For short frame sizes, performance gains can reach up to several dBs for high coding rates.

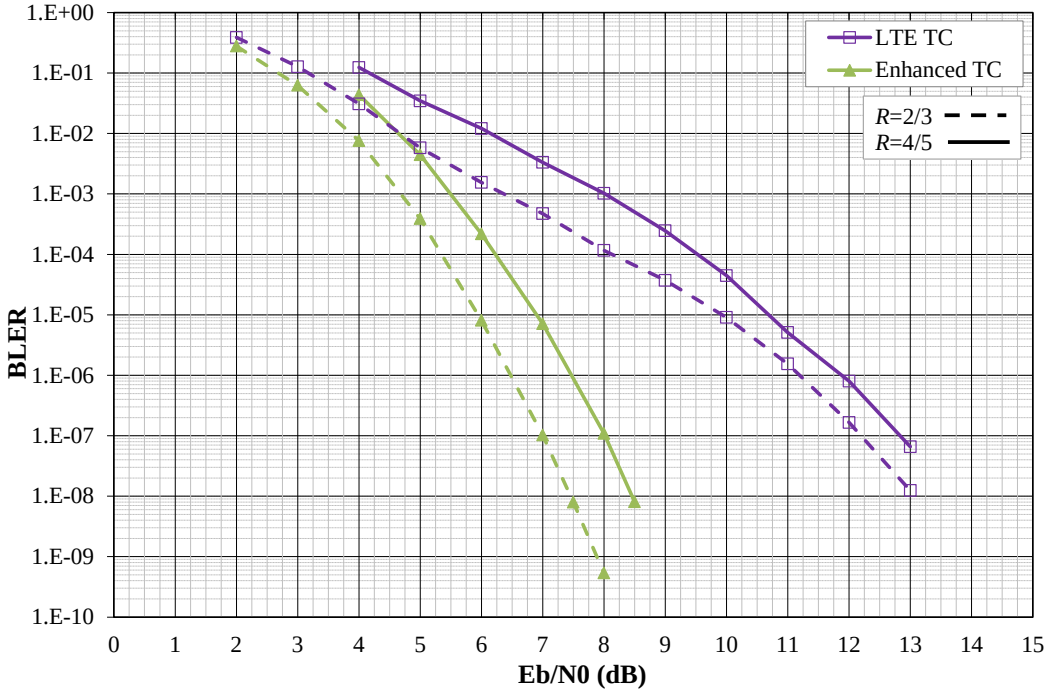

Figure 1. Performance comparison of the improved turbo code with the LTE turbo code in AWGN channel for coding rates 2/3 and 4/5 in terms of BLock Error Rate vs Eb/N0. BPSK modulation, block size *K* = 48 bits, 8 decoding iterations.

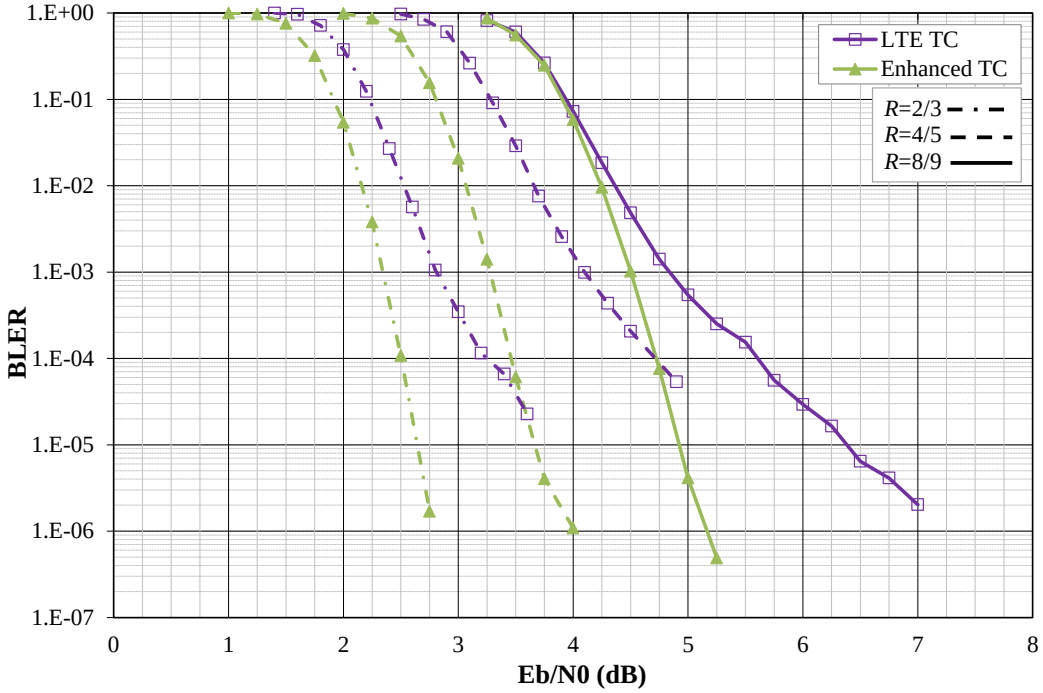

Figure 2. Performance comparison of the improved turbo code with the LTE turbo code in AWGN channel for coding rates 2/3, 4/5 and 8/9 in terms of BLock Error Rate vs Eb/N0. BPSK modulation, block size *K* = 1504 bits, 8 decoding iterations.

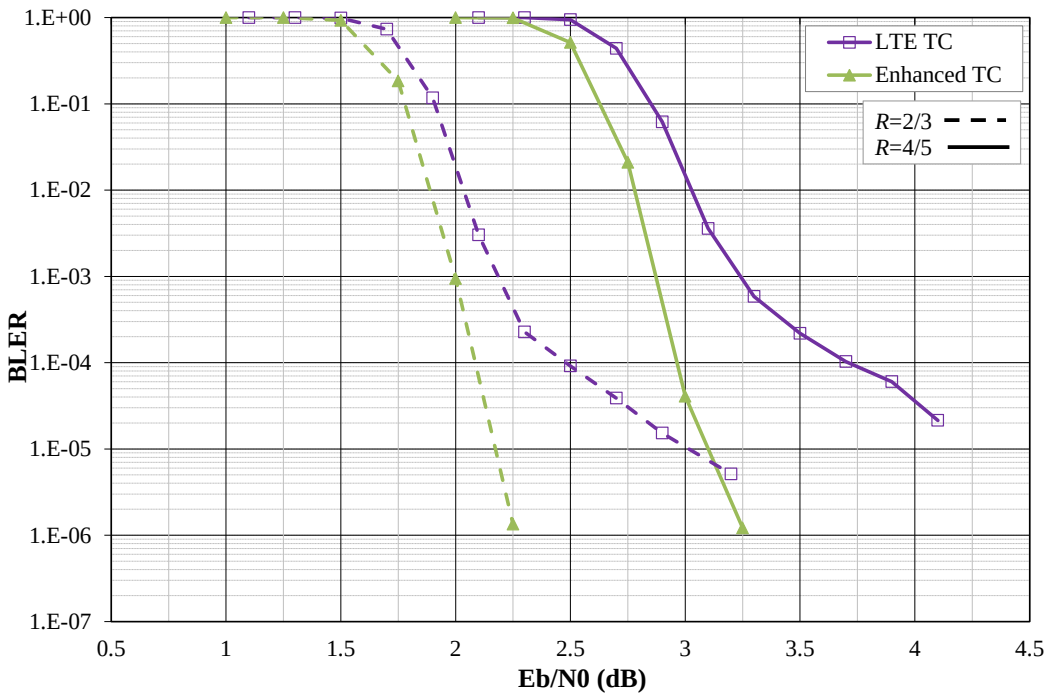

Figure 3. Performance comparison of the improved turbo code with the LTE turbo code in AWGN channel for coding rates 2/3 and 4/5 in terms of BLock Error Rate vs Eb/N0. BPSK modulation, block size *K* = 6144 bits, 8 decoding iterations.

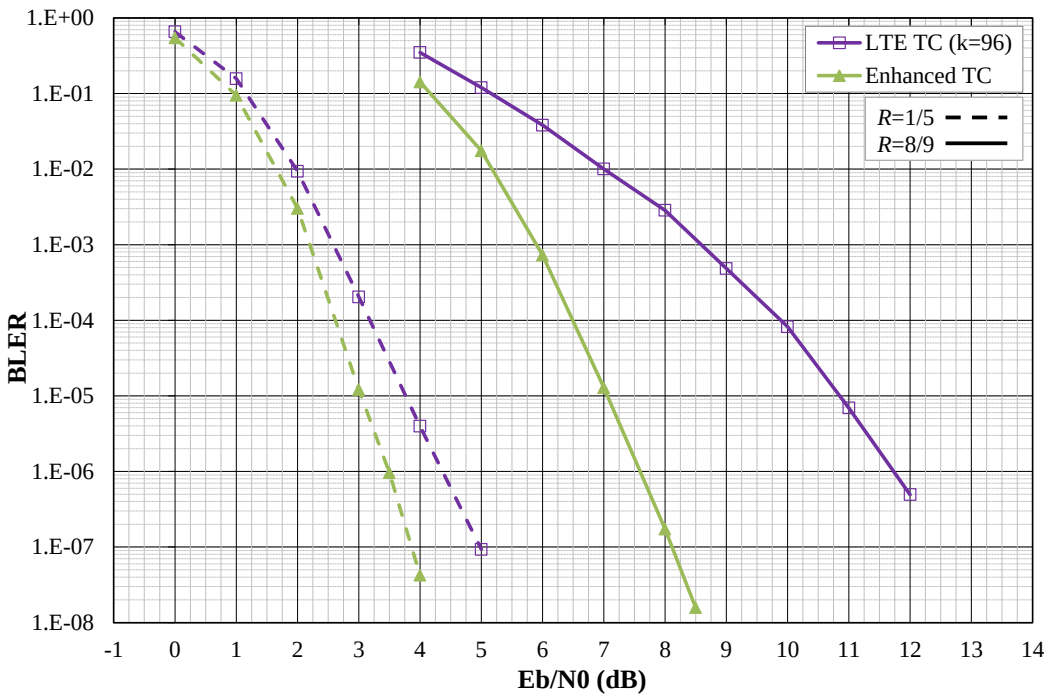

Figure 4. BLock Error Rate performance of the improved turbo code in AWGN channel for coding rates 1/5 (*K* = 100) and 8/9 (*K* = 96). BPSK modulation, 8 decoding iterations. Comparison with LTE turbo code (*K* = 96).

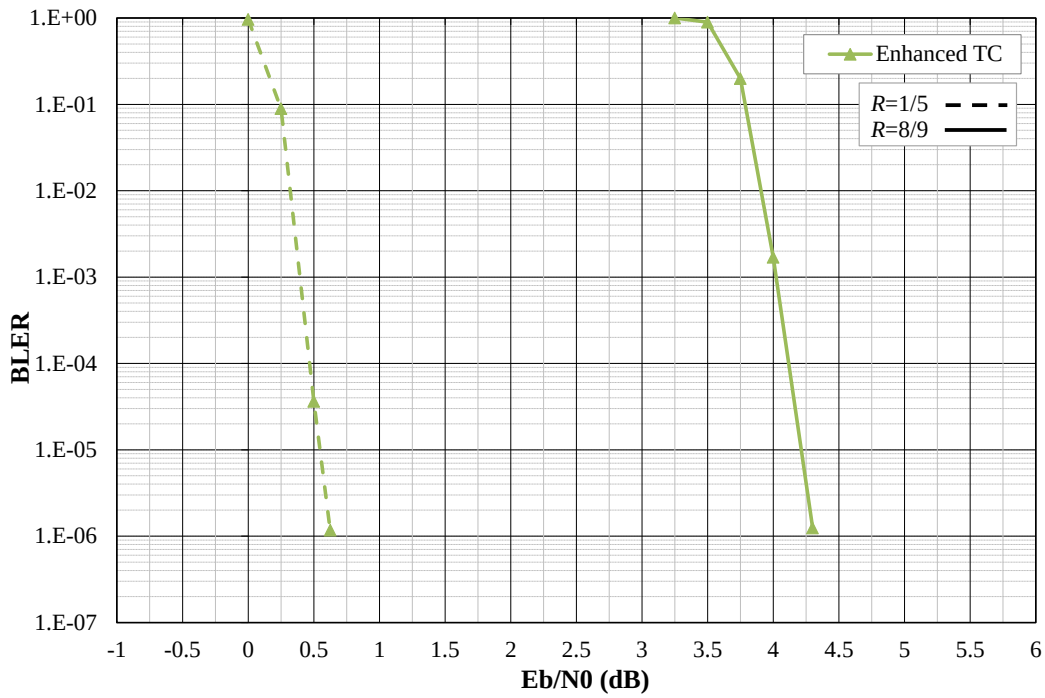

Figure 5. Block Error Rate performance of the improved turbo code in AWGN channel for coding rates 1/5 and 8/9. BPSK modulation, block size *K* = 8000 bits, 8 decoding iterations.

5 Conclusion

Legacy turbo codes are far from achieving their full potential due to non-optimized interleaver and puncturing schemes as well as trellis termination. The error floor can be significantly lowered thanks to the joint optimization of the interleaver and puncturing schemes as demonstrated by our Monte Carlo simulations. A new design of turbo code is perfectly fitted to fulfil the requirements of NR with a time to market advantage inherited from the legacy LTE turbo codes.

6 Observations and proposals

Observation 1: Turbo codes show native flexibility in code rates and frame sizes with a high implementation maturity.

Observation 2: Turbo codes can offer similar and often better performance than LDPC codes especially for short frame sizes.

Observation 3: LTE Turbo codes are far from achieving the full potential of Turbo codes mainly due to the error floor and trellis termination issues.

Observation 4: State-of-the-art comparisons between codes are inaccurate in most cases since they are limited to computational complexity. Memory requirements and number of memory accesses are important parameters to be further considered.

Observation 5: The number of supported code rate / frame size combinations has a large impact on the complexity of some family of codes such as LDPC codes.

Observation 6: Very high throughput (>20Gbps) turbo decoder implementations are being proposed in the literature.

Proposal 1: Use tail-biting for trellis termination

Proposal 2: Completely re-design the puncturing and interleaving scheme of turbo codes in order to fulfil the tight requirements of NR

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