Hybrid ARQ Scheme for UMTS LTE Based on Insertion Convolutional Turbo Codes

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***Abstract*—Mobile communication systems as, e.g, UMTS LTE perform rate matching and *Hybrid Automatic Repeat reQuest* (HARQ) to provide adequate decoding performance over a wide range of channel conditions. In UMTS LTE this is realized by means of a fixed rate convolutional Turbo code and a rate matching scheme based on bit puncturing and bit repetition. A promising alternative to convolutional Turbo codes with simple bit repetition are *Rate-Compatible Insertion Convolutional* (RCIC) Turbo codes which have proven considerable performance gains in systems without HARQ. Since modern systems conventionally employ HARQ, a novel HARQ scheme for UMTS LTE based on RCIC Turbo codes is presented in this paper. Extensive simulations have demonstrated that the conventional UMTS LTE HARQ scheme is outperformed by our novel HARQ scheme in terms of system throughput.**

I. Introduction

The latest release of the mobile radio standard UMTS LTE (Universal Mobile Telecommunications System Long Term Evolution) [1] or shortly LTE features flexible physical layer coding and modulation employing Turbo channel coding, rate matching by adaptive puncturing or repetition of encoded bits, *Hybrid Automatic Repeat reQuest* (HARQ) and a choice of complex signal constellations (QPSK, 16QAM, and 64QAM).

In particular, the realization of adaptive coding by means of a fixed rate channel code in conjunction with rate matching has attracted much attention in recent years. In modern communication systems, rate matching based on bit puncturing and bit repetition is often used, however, more promising approaches have been proposed. For instance, *rate-compatible pruned convolutional* Turbo codes, which are also known as *Rate-Compatible Insertion Convolutional* (RCIC) Turbo codes, have been invented by Collins and Hizlan [2] and have been investigated further, e.g., in [3]–[5] with regard to their *unequal error protection* (UEP) capability. Instead of employing repetition coding for flexibly decreasing the code rate, known bits (dummy bits) are inserted into the information bit sequence before convolutional Turbo encoding. At the receiver, these bits provide perfect *a priori* information which can be exploited by the *Soft-In/Soft-Out* (SISO) decoder for the decoding of the adjacent information bits. A first successful application of this concept to the LTE system has been presented in [6] revealing significant performance gains in terms of residual *frame error rate* (FER) compared to the conventional LTE rate matching for code rates $r_{\mathrm{RM}} < \frac{1}{3}$.

However, in systems employing HARQ, i.e., where *incremental redundancy* transmissions can be carried out, the full exploitation of the potential of RCIC codes is more challenging. Dummy bits are inserted before Turbo encoding in case a target code rate which is lower than the code rate of the employed Turbo code is desired. Higher code rates are achieved without dummy bit insertion by bit puncturing. In case of decoding failures, additional transmissions are requested by the receiver lowering the effective code rate after rate matching and HARQ. However, even if the effective code rate after HARQ drops below the code rate of the employed Turbo code, the advantages of the dummy bit insertion cannot be exploited. This is due to the fact that no code rate adaptation can be performed during HARQ by means of dummy bit insertion since the fraction of inserted dummy bits is fixed after Turbo encoding. Therefore, bit repetition is performed instead which results in a performance identical to the conventional LTE rate matching.

In this contribution, we propose a novel HARQ scheme for LTE based on RCIC codes which copes with the above mentioned performance limitation. It comprises

- a scheme which exploits the potential of RCIC codes as soon as the effective code rate after rate matching and HARQ drops below the code rate of the fixed rate Turbo code. This code rate does not have to be known before Turbo encoding since the fraction of effective dummy bits can be adapted accordingly during the HARQ process.
- a low complexity implementation based on a modified LTE ring buffer,
- a new dummy bit interleaver which enables the optimal exploitation of the dummy bits at the decoder.

This paper is structured as follows: In Sec. II, the conventional LTE rate matching procedure is introduced. Sec. III describes the fundamentals of RCIC Turbo codes which are used in Sec. IV for our novel HARQ scheme. Finally, the novel HARQ scheme is evaluated in terms of system throughput in Sec. V.

II. Rate Matching and HARQ in LTE

Rate matching in LTE [1] is realized by bit puncturing and bit repetition after convolutional Turbo coding. According to Fig. 1, a frame $\mathbf{b} = (b_1, \ldots, b_m, \ldots, b_M)$ of M information bits is encoded by a systematic rate-$\frac{1}{3}$ Turbo encoder consisting of two *Parallel Concatenated Convolutional Codes*

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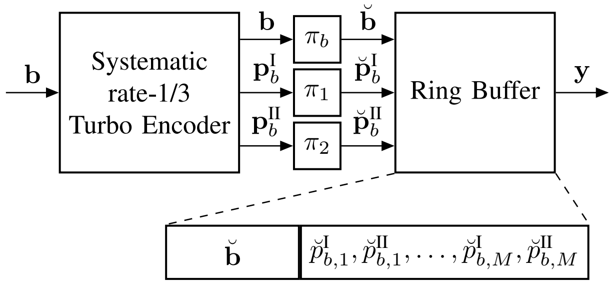

Fig. 1. Rate matching (adaptive coding) in LTE.

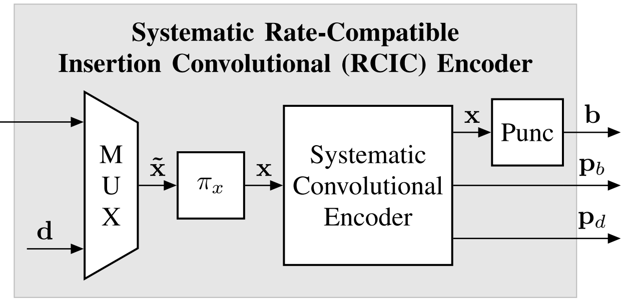

Fig. 2. Structure of an systematic rate-compatible insertion convolutional (RCIC) encoder.

(PCCCs) with octal generator polynomials $\mathbf{G}_{\text{CC}} = (1, 15/13)_8$ each generating one parity bit per information bit.

The encoded bits are then separated into three streams: The systematic (uncoded) information bits $\mathbf{b}$ and the parity bits of the two constituent encoders $\mathbf{p}_b^{\text{I}} = (p_{b,1}^{\text{I}}, \ldots, p_{b,m}^{\text{I}}, \ldots, p_{b,M}^{\text{I}})$ and $\mathbf{p}_b^{\text{II}} = (p_{b,1}^{\text{II}}, \ldots, p_{b,m}^{\text{II}}, \ldots, p_{b,M}^{\text{II}})$, respectively. For an efficient and easy to implement rate matching, the three streams are individually interleaved by the interleavers π_b, π_1 and π_2 and written to a ring buffer. At first, all systematic bits $\breve{\mathbf{b}}$ are written to the ring buffer. Then the parity bits of both streams $\breve{\mathbf{p}}_b^{\text{I}}$ and $\breve{\mathbf{p}}_b^{\text{II}}$ are interlaced and also written to the ring buffer according to the structure shown in Fig. 1. Finally, a block $\mathbf{y} = (y_1, \ldots, y_n, \ldots, y_N)$ of N encoded bits is selected for transmission resulting in an effective code rate $r_{\text{RM}} = \frac{M}{N}$. The size N of the block of encoded bits is determined by the scheduler according to the user's instantaneous channel quality, the user's requested throughput, maximum delay, target FER and the current load of the radio cell. Thereby the scheduler implicitly influences the code rate r_{RM} of the user. A block size $N < 3 \cdot M$ results in a code rate $r_{\text{RM}} > \frac{1}{3}$, whereas if N is sufficiently large, the code rate r_{RM} can take values $r_{\text{RM}} < \frac{1}{3}$ by repetition of systematic and parity bits. Consequently, bit puncturing and bit repetition is implicitly performed by reading out the ring buffer. The bits selected for transmission are mapped to complex symbols using either QPSK, 16QAM, or 64QAM prior to transmission.

At the receiver, reliability information in form of *Log-Likelihood Ratio*s (LLRs) [7] on the systematic information bits $\mathbf{b}$ and the parity bits $\mathbf{p}_b^{\text{I}}$ and $\mathbf{p}_b^{\text{II}}$ can be exploited by the Turbo decoder using the *Bahl-Cocke-Jelinek-Raviv* (BCJR) algorithm [8] for soft channel decoding.

To account for decoding failures, the LTE HARQ scheme allows for up to $R = 4$ transmissions of different combinations of systematic and parity bits, the so-called *Redundancy Versions* (RVs). According to [1], the initial reading position θ_ρ of a distinct RV ρ $(1 \leq \rho \leq R)$ is given by

$$\theta_\rho = A\left(2(\rho-1)\left\lceil\frac{3(M+4)}{8A}\right\rceil+2\right)+1,\ A = \left\lceil\frac{M+4}{32}\right\rceil \quad (1)$$

Two important conclusions can be drawn from (1):

(a) The initial reading position of the first RV is given by $\theta_1 = 2 \cdot A + 1 \neq 1$, i.e., the first RV does not start at the beginning of the ring buffer.
(b) The ring buffer is not read out continuously, i.e., the current RV ρ does not start at the end of the previous RV $\rho - 1$. This may result in a rate matching procedure performing bit puncturing and repetition at the same time due to overlapping RVs.

III. Rate-Compatible Insertion Convolutional (RCIC) Turbo Codes

In general, parallel or serially concatenated RCIC codes [2], [3] are referred to as RCIC Turbo codes. They can simply construct lower code rates based on fixed rate convolutional component codes by inserting known bits (dummy bits) into the information bit sequence before convolutional encoding.

a) RCIC Encoder: The structure of a *systematic* insertion convolutional component encoder as it will be employed in our novel HARQ scheme is depicted in Fig. 2. The multiplexed vector $\tilde{\mathbf{x}} = [\mathbf{b}, \mathbf{d}]$, containing the information bits $\mathbf{b}$ and the dummy bits $\mathbf{d} = (d_1, \ldots, d_l, \ldots, d_L)$, is interleaved by an interleaver π_x. Without loss of generality, zeros are chosen as dummy bits $(d_l = 0,\ 1 \leq l \leq L)$. In order to optimally exploit the dummy bit information at the decoder, the dummy bits have to be distributed equidistantly within a frame [9]. This can be realized by the following algorithm:

Algorithm 1 Dummy bit insertion

Initialize: $x_k = 0$ for $1 \leq k \leq K$
  for all m such that $1 \leq m \leq M$ **do**
    $x_k = b_m$ with $k = \text{round}\left((m-1) \cdot \frac{M+L}{M}\right)$
  end for
  (dummy bits $d_l = 0$ at all other position provided by initialization step)

The resulting sequence $\mathbf{x} = (x_1, \ldots, x_k, \ldots, x_K)$ of length $K = M + L$ is then encoded by a systematic convolutional encoder with generator polynomials $\mathbf{G}_{\text{CC}}$ and code rate r_{CC}. At the output, the systematic bits $\mathbf{x}$, the parity bits $\mathbf{p}_b$ of length $(r_{\text{CC}}^{-1} - 1) \cdot M$ corresponding to the information bits $\mathbf{b}$ and the parity bits $\mathbf{p}_d$ of length $(r_{\text{CC}}^{-1} - 1) \cdot L$ corresponding to the dummy bits $\mathbf{d}$ are obtained. Puncturing is used within the systematic branch in order to eliminate all systematic dummy bits. These bits are known in advance at the receiver and, thus, do not have to be transmitted over the channel.

Throughout this contribution, Turbo coding based on PCCCs is considered. For a system employing convolutional Turbo encoding without dummy bit insertion, the code rate is given by $r_{\text{TC}} = 2 * r_{\text{CC}} - 1$. In case of parallel concatenated

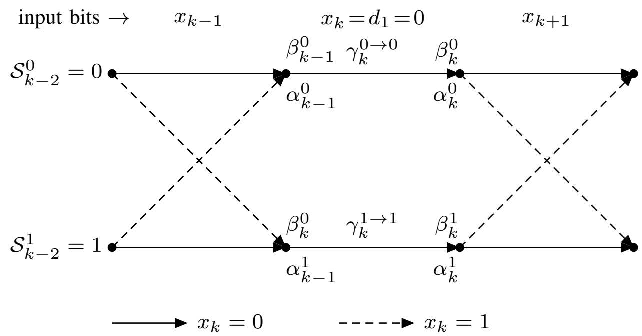

Fig. 3. Trellis diagram for a recursive convolutional code with generator polynomial $G_R = (2/3)_8$. One dummy bit $d_1 = 0$ is inserted at time instance k.

RCIC codes, the code rate can be determined by

$$r_{\text{IC}} = \frac{M}{K \cdot r_{\text{TC}}^{-1} - L}. \tag{2}$$

It is worth noting that $0 < r_{\text{IC}} \leq r_{\text{TC}}$, i.e., only lower code rates can be provided by RCIC turbo codes. Consequently, they are an alternative to rate-compatible convolutional Turbo codes based on bit repetition.

b) RCIC Decoder: The decoder receives channel-related LLR vectors $\mathbf{L}(\mathbf{b})$, $\mathbf{L}(\mathbf{p}_b)$ and $\mathbf{L}(\mathbf{p}_d)$ for the systematic bits and all parity bits. Furthermore, perfect *a priori* information about the dummy bits is provided to the decoder. This results in a pruned trellis diagram as exemplarily depicted in Fig. 3 for a recursive convolutional code with recursive generator polynomial $G_R = (2/3)_8$ where one dummy bit $d_1 = 0$ is inserted into the input frame at time instance k. The pruned trellis at each dummy bit position in conjunction with the additional channel-related information $\mathbf{L}(\mathbf{p}_d)$ can then be exploited during the BCJR decoding of the information bits $\mathbf{b}$. Considering the trellis diagram of a conventional code with constraint length $J + 1$ (c.f. Fig. 3, $J = 1$), at a dummy bit position k half of the state transitions disappear. Furthermore, each state $\mathcal{S}^i_{k-1}$ ($0 \leq i < 2^J$) is connected with exactly one succeeding state $\mathcal{S}^j_k$ ($0 \leq j < 2^J$). The forward and backward recursion α^j_k and β^i_k at time instance k can be expressed in the logarithmic domain for each valid transition $\mathcal{S}^i_{k-1} \to \mathcal{S}^j_k$ according to

$$\alpha^j_k = \gamma^{i\to j}_k + \alpha^i_{k-1}, \quad \beta^i_{k-1} = \gamma^{i\to j}_k + \beta^j_k. \tag{3}$$

The innovations $\gamma^{i\to j}_k$ at a dummy bit position k for a systematic convolutional code are generally given by

$$\gamma^{i\to j}_k = \frac{1}{2} \sum_{i\in\mathbb{I}} p_{d,i} L(p_{d,i}) \tag{4}$$

exploiting the channel-related reliabilities $\mathbf{L}(\mathbf{p}_d)$. $\mathbb{I}$ denotes the set of parity bits which participate at time instance k. Note that the perfect knowledge of the dummy bit $d_1 = 0$ has already been taken into account by the pruned state transitions. It can be concluded from (3) and (4) that RCIC codes only gain from the additional channel-related information provided by the parity bits $\mathbf{p}_d$ generated at each dummy bit position. In other words, if $\mathbf{p}_d$ would be completely punctured, (3) and (4) reduces to $\gamma^{i\to j}_k = 0$, $\alpha^j_k = \alpha^i_{k-1}$ and $\beta^i_{k-1} = \beta^j_k$ which implies that the effect of the dummy bits disappears. This behavior is extremely beneficial for our novel HARQ scheme presented in the next section due to the following properties:

- Low rate RCIC encoding with dummy bit puncturing provides equal performance compared to a single RCIC code without dummy bit puncturing and the same effective code rate r_{RM}.
- The effective code rate r_{RM} does not have to be known at the RCIC encoder. It can be controlled after encoding without any loss in performance by just puncturing the respective number of parity bits $\mathbf{p}_d$. This ensures an extremely high flexibility in terms of code rate adaptation.

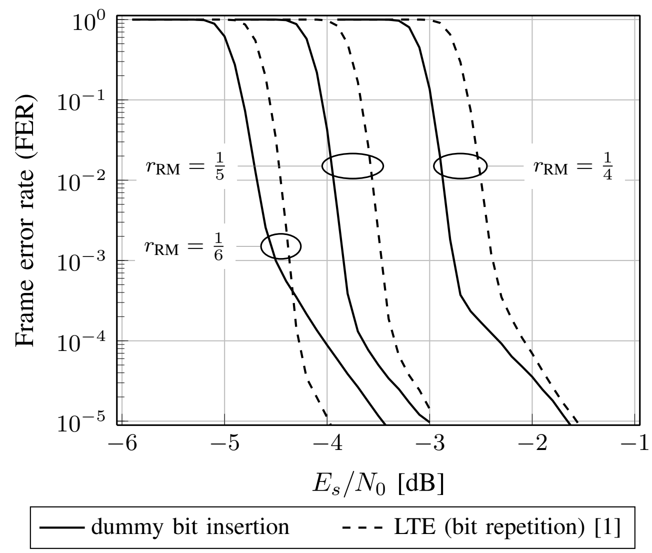

Fig. 4. Comparison of the conventional LTE rate matching (bit repetition) with the modified LTE rate matching based on dummy bit insertion.

The performance gain in terms of residual *frame error rate* (FER) for a modified LTE system employing dummy bit insertion compared to the conventional system employing bit repetition is highlighted in Fig. 4. This evaluation has been conducted for a frame size $M = 6144$, overall target code rates after rate matching $r_{\text{RM}} \in \{\frac{1}{4}, \frac{1}{5}, \frac{1}{6}\}$, QPSK modulation and transmission over an AWGN channel. It has been observed that a gain of approximately 0.3–0.4 dB can be realized by RCIC codes for $\frac{1}{5} \leq r_{\text{RM}} \leq \frac{1}{3}$ within the waterfall region. For $r_{\text{RM}} = \frac{1}{6}$, the gain within the waterfall region is reduced and a considerable error floor is visible.

IV. Novel Hybrid ARQ Scheme

According to Fig. 4, the application of RCIC Turbo codes instead of convolution Turbo coding with bit repetition as in LTE provides considerable gains in the waterfall region in terms of residual FER for code rates $\frac{1}{5} \leq r_{\text{RM}} < \frac{1}{3}$. Using such a code in conventional HARQ schemes is of minor benefit since these gains can only be realized if the code rate selected for the initial transmission lies in the above mentioned range. If code rates $r_{\text{RM}} \geq \frac{1}{3}$ are initially chosen and additional transmissions are requested due to decoding errors, no benefit can be expected although the effective code rate after rate

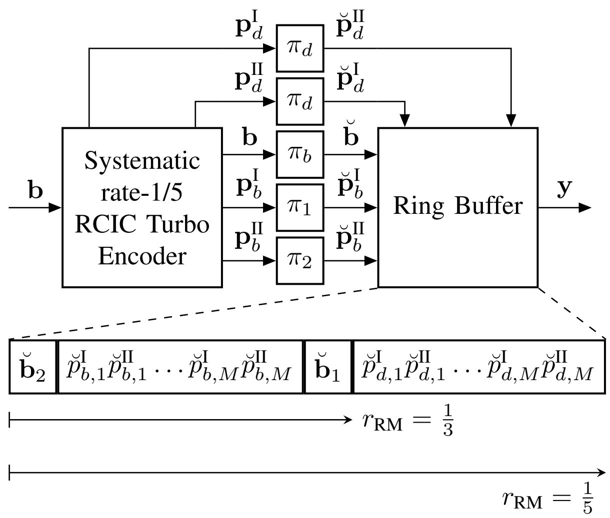

Fig. 5. Low rate RCIC Turbo code with ring buffer implementation used in the novel HARQ scheme (see also Fig. 2).

matching and HARQ may be within the desired range. In this case only bit repetition is employed and the modified system reduces to the conventional one since the fraction of dummy bits cannot be adapted during HARQ.

Therefore, we propose a novel HARQ system for LTE which benefits from the gains provided by dummy bit insertion as soon as the effective code rate after rate matching and HARQ drops below the threshold $\frac{r_{\text{RM}}}{\rho} = \frac{1}{3}$ (ρ is number of transmissions). Furthermore, an effective ring buffer implementation, which is similar to the LTE realization, has been developed and will be described in what follows.

The structure of the novel rate matching unit is shown in Fig. 5. The information bit vector $\mathbf{b}$ is encoded by an RCIC Turbo encoder with fixed code rate $r_{\text{IC}} = \frac{1}{5}$ which is the lowest useful code rate according to Fig. 4. The LTE Turbo code is employed as mother code. Taking Algorithm 1 and Equation (2) into account, this results in an equidistant insertion of $M = L$ dummy bits. Five streams are generated by the encoder: The systematic information bits $\mathbf{b}$, the parity bits $\mathbf{p}_b^{\text{I}}$ and $\mathbf{p}_b^{\text{II}}$ corresponding to the information bits and the parity bits $\mathbf{p}_d^{\text{I}}$ and $\mathbf{p}_d^{\text{II}}$ corresponding to the dummy bits. All streams are individually interleaved and written to the ring buffer according to the structure depicted in Fig. 5. The interleaved information bit vector $\breve{\mathbf{b}}$ is separated into two streams $\breve{\mathbf{b}}_1 = (\breve{b}_1, \ldots, \breve{b}_{\theta_1 - 1})$ and $\breve{\mathbf{b}}_2 = (\breve{b}_{\theta_1}, \ldots, \breve{b}_M)$ with $\breve{\mathbf{b}} = [\breve{\mathbf{b}}_1, \breve{\mathbf{b}}_2]$ where θ_1 is determined by (1). The modified initial reading position θ'_ρ of a distinct redundancy version ρ ($1 \leq \rho \leq R$) is now given by

$$\theta'_\rho = \text{mod}\left(((\rho - 1) \cdot N), 5M\right) + 1, \tag{5}$$

where N is the length of each RV, $5M$ the size of the ring buffer and $\text{mod}(\cdot, \cdot)$ signifies the modulo operation. Consequently, it can be concluded that

(a) the first RV starts at the beginning of the ring buffer,
(b) the next RV ρ starts at the end of the previous RV $\rho - 1$.

The special structure in conjunction with property (a) guarantees that the first RV of the modified systems equals the first RV of the conventional LTE system for any rates $r_{\text{RM}} \geq \frac{1}{3}$. For code rates $\frac{1}{5} \leq r_{\text{RM}} \leq \frac{1}{3}$, the RCIC decoder can benefit from the dummy bit insertion since a fraction of parity bits $\mathbf{p}_d^{\text{I}}$ and $\mathbf{p}_d^{\text{II}}$ are additionally transmitted (c.f. Fig. 5). In order to provide effective code rates $\frac{r_{\text{RM}}}{\rho} < \frac{1}{5}$ after ρ transmissions, the ring buffer is continuously read out resulting in repetition of systematic and parity bits.

A key element in the novel HARQ scheme is the interleaver π_d which rearranges the position of the parity bits $\mathbf{p}_d^{\text{I}}$ and $\mathbf{p}_d^{\text{II}}$ within the ring buffer according to a bijective interleaver mapping $l \leftrightarrow \Gamma(l)$: $\breve{p}_{d,\Gamma(l)} = p_{d,l}$. As described in Sec. III, best performance can be expected if all bits which are read out for transmission are equidistantly distributed within the frame. Accordingly, we have developed a low complexity, recursive algorithm which can construct the required interleaver mapping for any interleaver size on the fly saving a lot of storage space. The core algorithm only operates on block sizes 2^Λ, $\Lambda \in \mathbb{N}$. Therefore, if necessary, filler bits are appended to the vectors $\mathbf{p}_d^{\text{I}}$ and $\mathbf{p}_d^{\text{II}}$ before interleaving. Obviously, these bits are removed again after interleaving. In each step λ, the core algorithm determines recursively an index vector $\mathbf{v}_\lambda$ ($0 \leq \lambda \leq \Lambda$) for a block size 2^λ:

Algorithm 2 Dummy bit index vector v_Λ for block sizes 2^Λ

Initialize: $\mathbf{v}_0 = 1$
  for all λ such that $1 \leq \lambda \leq \Lambda$ **do**
    $\mathbf{v}_\lambda = [(2\mathbf{v}_{\lambda-1} - 1), 2\mathbf{v}_{\lambda-1}]$
  end for

The vector $\mathbf{v}_\Lambda$ contains the interleaver mapping for block sizes 2^Λ. The removal of the filler bits results in the vector $\mathbf{v}'_\Lambda = (v'_{\Lambda,1}, \ldots, v'_{\Lambda,l}, \ldots, v'_{\Lambda,L})$ which provides the desired interleaver mapping $\Gamma(l) = v'_{\Lambda,l}$, $1 \leq l \leq L$. For the sake of clarity, the following example is considered: An interleaver mapping for a block size of $L = 2^4 = 16$ bits ($\mathbf{v}'_\Lambda = \mathbf{v}_\Lambda$) shall be constructed by means of Algorithm 2. After the initialization step $\mathbf{v}_0 = 1$, the recursion generates step wise the desired index vector $\mathbf{v}_4$:

$$\mathbf{v}_1 = (1, 2) \tag{6}$$
$$\mathbf{v}_2 = (1, 3, 2, 4) \tag{7}$$
$$\mathbf{v}_3 = (1, 5, 3, 7, 2, 6, 4, 8) \tag{8}$$
$$\mathbf{v}_4 = (1, 9, 5, 13, 3, 11, 7, 15, 2, 10, 6, 14, 4, 12, 8, 16). \tag{9}$$

Then rate matching is exemplarily performed with

(a) a code rate $r_{\text{RM}} = \frac{2}{7}$ resulting in the transmission of $\frac{1}{4}$ of the parity bits $\mathbf{p}_d^{\text{I}}$ and $\mathbf{p}_d^{\text{II}}$. For this case, the effective dummy bit index vector is given by $\tilde{\mathbf{v}}_4 = (1, 9, 5, 13)$.
(b) a code rate $r_{\text{RM}} = \frac{1}{4}$ resulting in the transmission of $\frac{1}{2}$ of the parity bits $\mathbf{p}_d^{\text{I}}$ and $\mathbf{p}_d^{\text{II}}$. For this case, the effective dummy bit index vector is given by $\tilde{\mathbf{v}}_4 = (1, 9, 5, 13, 3, 11, 7, 15)$.

Consequently, the channel-related information $\mathbf{L}(\mathbf{p}_d^{\text{I}})$ and $\mathbf{L}(\mathbf{p}_d^{\text{II}})$ provided to the corresponding RCIC decoder is equidistantly distributed. In these cases, the system performance will be equivalent to a system only consisting of a single RCIC code with fixed code rate $r_{\text{IC}} = \frac{2}{7}$ and $r_{\text{IC}} = \frac{1}{4}$, respectively. This demonstrates that the specific construction rule of the interleaver allows to control the effective code rate after encoding without any performance degradation. This property is essential for the effectiveness of the proposed HARQ scheme. Furthermore, for any other fractions at least a homogeneous distribution of the dummy bits is provided. For example, a code rate $r_{\mathrm{RM}} = \frac{2}{9}$ results in the transmission of $\frac{3}{4}$ of the parity bits $\mathbf{p}_d^{\mathrm{I}}$ and $\mathbf{p}_d^{\mathrm{II}}$. In this case, the parity bits which are not selected for transmission correspond to the indexes $(4, 12, 8, 16)$ and are thus equidistantly distributed.

V. Evaluation

The conventional LTE system as well as the novel RCIC based HARQ system have been simulated in an AWGN environment. Simulations were conducted with 10 Turbo iterations, a maximum of $R = 4$ transmissions and with modulation and coding schemes as indicated in Table I where I is the number of code bits per modulation symbol.

TABLE I
Modulation and coding schemes (MCS).

Modulation	Code rates
QPSK ($I = 2$)	$r_{\mathrm{RM}} \in \{\frac{1}{6}, \frac{1}{5}, \frac{1}{4}, \frac{1}{3}, \frac{1}{2}, \frac{2}{3}, \frac{3}{4}\}$
16QAM ($I = 4$)	$r_{\mathrm{RM}} \in \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}\}$
64QAM ($I = 6$)	$r_{\mathrm{RM}} \in \{\frac{1}{2}, \frac{2}{3}, \frac{3}{4}, \frac{4}{5}\}$

Both systems are compared in terms of their throughput which is defined for a specific MCS as

$$\mathcal{T}_{\mathrm{mcs}} = (1 - \mathrm{FER}) \cdot \frac{r_{\mathrm{RM}} \cdot I}{\bar{R}} \qquad (10)$$

with $\bar{R}$ denoting the average number of required transmissions and FER the frame error rate after the last transmission. According to Table I, 15 different throughput curves each corresponding to one specific modulation and coding scheme are obtained.

Fig. 6 shows the envelope $\mathcal{T}_{\mathrm{max}}$ of these throughput curves for the conventional LTE HARQ system based on bit puncturing and bit repetition (- - -) as well as for the novel LTE HARQ scheme (—) based on bit puncturing and dummy bit insertion. Since a wide range of channel conditions is covered by both systems, the complete SNR range is devided into a lower SNR range (upper figure) and a higher SNR range (lower figure). According to Fig. 6, dummy bit insertion is most effective in the lower SNR range. For these channel conditions, the novel approach performs better than or equal to the conventional LTE HARQ scheme with gains up to $\Delta\mathrm{SNR} = 0.7\,\mathrm{dB}$. In the higher SNR range the dummy bit insertion has less effect on the maximum throughput $\mathcal{T}_{\mathrm{max}}$ since MCS modes comprising higher code rates ($\frac{1}{2}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{4}{5}$) are mainly employed. Consequently, improvements in system throughput can only be expected if the maximum throughput is provided by such an MCS after carrying out additional transmissions which lead to an effective code rate lower than $\frac{1}{3}$. Nevertheless, gains up to $\Delta\mathrm{SNR} = 0.95\,\mathrm{dB}$ are possible.

In Fig. 7 the throughput for three distinctive modulation and coding schemes is depicted exemplarily. Again, the gains of the novel LTE HARQ scheme are obvious: for more than one transmission, the novel system provides a much better performance, e.g., $\Delta\mathrm{SNR} = 1.5\,\mathrm{dB}$ for 64QAM with code rate $r_{\mathrm{RM}} = \frac{1}{2}$. Consequently, the novel HARQ scheme benefits from the dummy bit insertion method as soon as the effective code rate after rate matching and HARQ drops below the code rate of the mother code ($r_{\mathrm{CC}} = \frac{1}{3}$). This is the major gain compared to conventional systems based on RCIC codes in which the code rate after encoding and rate matching has to be known at the RCIC encoder, i.e., before HARQ has been carried out. These systems cannot adapt their code rate by dummy bit insertion afterwards if additional RV transmissions are requested by the receiver. In particular for systems without perfect channel state information, the novel LTE HARQ system outperforms the conventional one. In this case, additional RV transmissions have to be carried out more frequently resulting in more frequently and even higher throughput gains.

VI. Conclusions

We have proposed a novel HARQ scheme for LTE based on RCIC Turbo codes which outperforms the conventional HARQ scheme of LTE. The effectiveness in terms of performance and implementation effort is achieved by the combination of a low rate RCIC code with a low complexity ring buffer which is based on the special realization of the dummy bit interleaver as described in Sec. IV. This setup enables the exploitation of the dummy bits in an optimal sense, i.e., all dummy bits which are taken into account during decoding are equidistantly distributed within the frame independent of the effective code rate after rate matching and HARQ. Furthermore, the LTE-like ring buffer structure simplifies the integration of the proposed HARQ scheme in future mobile communication systems since only minor transceiver modifications are required.

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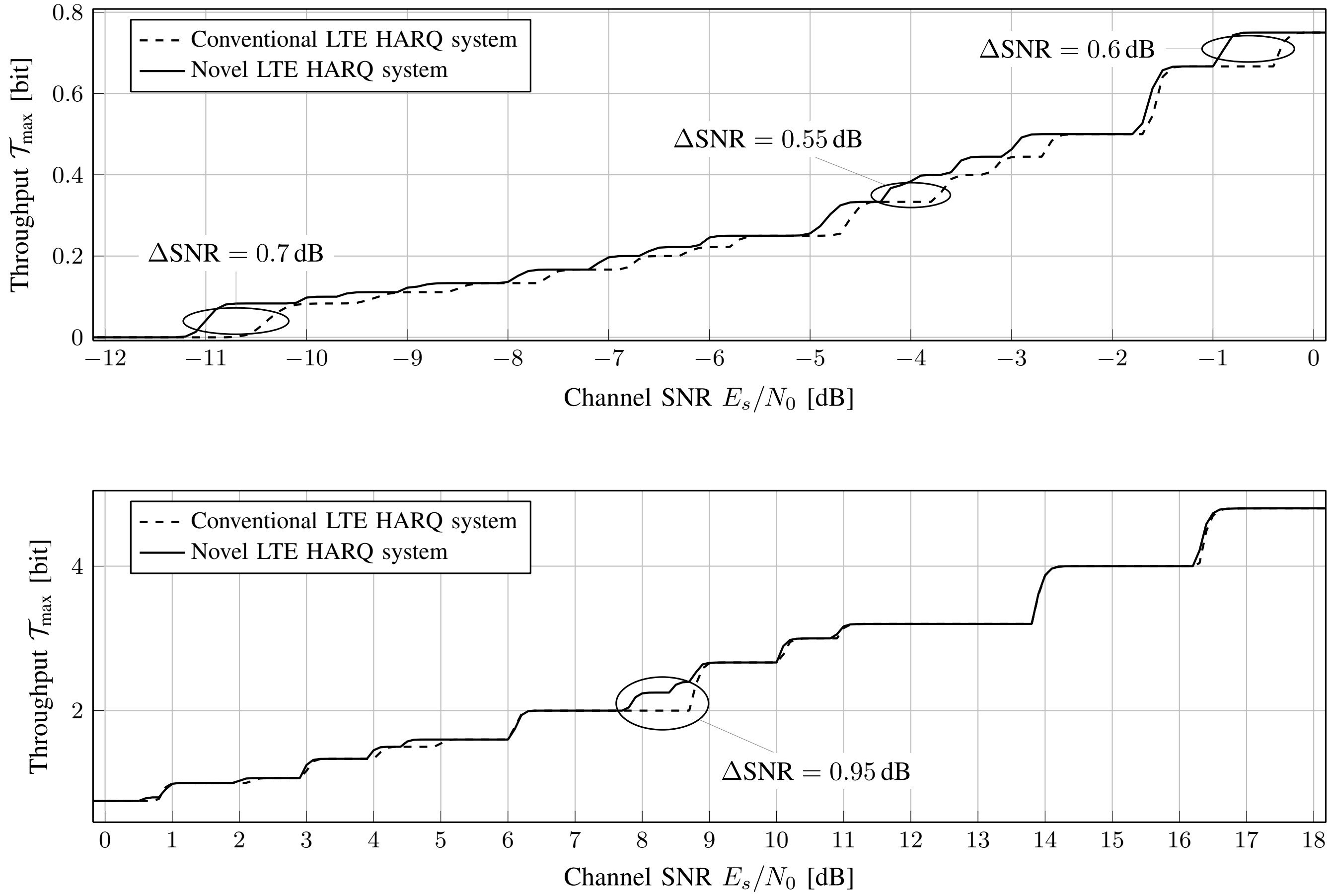

Fig. 6. Maximum system throughput (envelope) of the novel LTE HARQ system compared to the conventional LTE HARQ system.

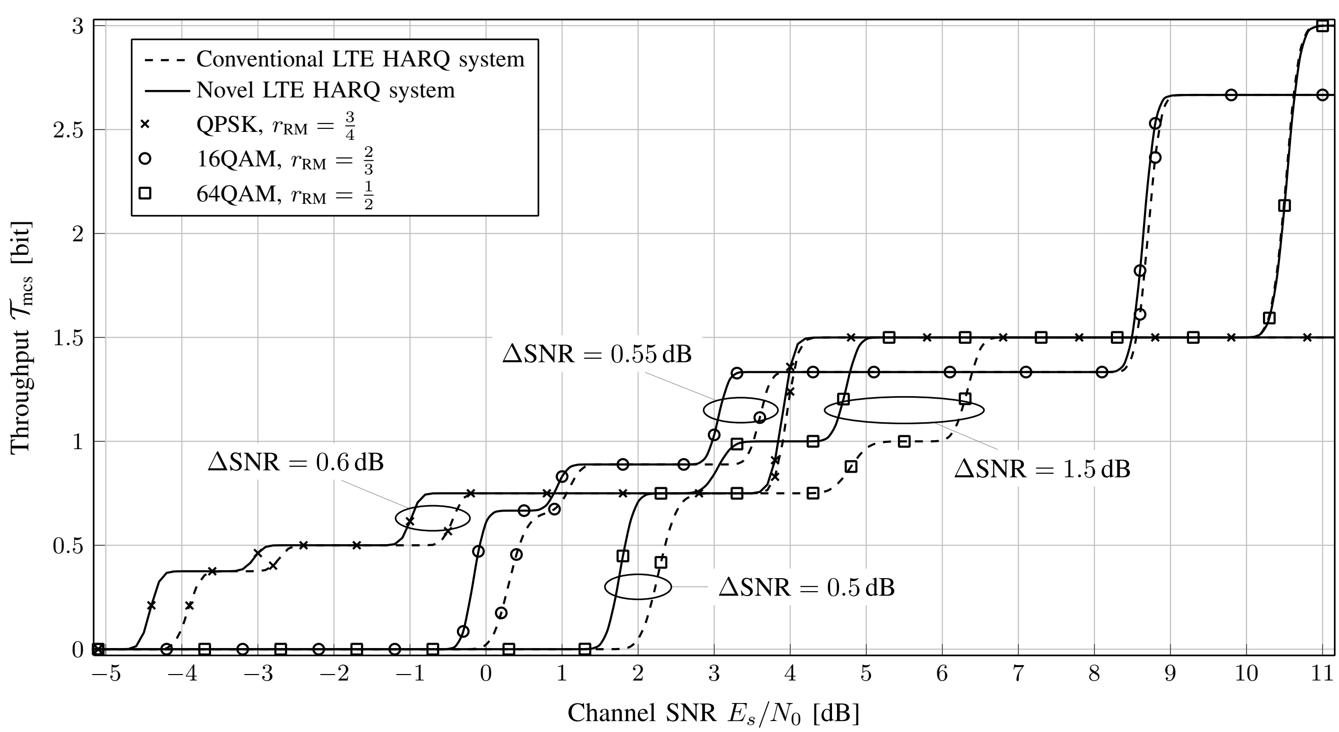

Fig. 7. System throughput of the novel LTE HARQ system compared to the conventional LTE HARQ system for three different modes.