Low Complexity Coding and Modulation for UMTS LTE: BICM-ID with Repetition Coding

Helge Lüders, Andreas Minwegen, and Peter Vary
Institute of Communication Systems and Data Processing (ind)
RWTH Aachen University, Germany
{lueders|minwegen|vary}@ind.rwth-aachen.de

Abstract— **In this contribution we focus on the physical layer of UMTS Long Term Evolution (LTE) and propose an alternative transceiver concept which might be considered for further extensions of the standard. A simple repetition code is combined with a complex mapper with bit doping resulting in a Bit-Interleaved Coded Modulation with Iterative Decoding (BICM-ID) scheme. Allowing feed-back based multiple transmissions of the same coded frame similar to the hybrid automatic repeat-request scheme employed in UMTS LTE, we show that the performance in terms of goodput (error-free throughput) of the proposed BICM-ID scheme is comparable to UMTS LTE for high order modulation schemes (16QAM, 64QAM) for the considered cases, while the receiver complexity is significantly reduced.**

I. Introduction

The OFDM based UMTS *Long Term Evolution* (LTE) standard is considered the first step toward the goals set by the Next Generation Mobile Networks Alliance (NGMN). Its physical layer specification [1], [2] combines high spectral efficiency and flexibility for an optimum use of radio resources. However, while the search for even more flexible and efficient transmission schemes is ongoing, complexity issues are widely discussed to tackle the problem of energy consumption in all entities involved in radio access.

In this contribution we propose a *Bit-Interleaved Coded Modulation with Iterative Decoding* (BICM-ID) scheme [3] based on simple repetition coding and complex symbol mapping with so-called *bit doping* [4], [5] and compare its performance to UMTS LTE. It turns out that for higher order modulation schemes (16QAM, 64QAM) a comparable performance is achieved while the algorithmic complexity is significantly reduced.

II. System Model

In this section we briefly introduce the relevant physical layer features of the implemented UMTS LTE transceiver and introduce our alternative approach.

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Andreas Minwegen is now with the Institute for Integrated Signal Processing Systems, RWTH Aachen University.

A. UMTS LTE

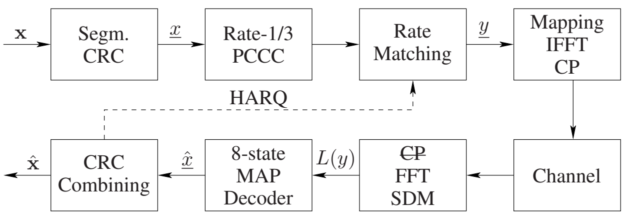

Fig. 1. Physical Layer of LTE.

The block diagram of the baseband UMTS LTE transceiver implementation is sketched in Fig. 1. A stream of binary input data $\mathbf{x}$ is segmented into data frames $\underline{x}$ of length l_{bl}, where the maximum value for l_{bl} is limited by the standard [2] to 6144 bit including a 24 bit Cyclic Redundancy Check (CRC), which is added to each data frame. These data frames are then encoded by a systematic rate-$\frac{1}{3}$ turbo coder consisting of two parallel concatenated convolutional codes (PCCC) which are systematic and recursive with octal generator polynomial $G = \{1, 15/13\}_8$. Each constituent encoder generates one parity bit per data bit. For an efficient and easy to implement rate matching the encoded streams (one containing the systematic bits and two parity bit streams) are individually interleaved and written to a ring buffer [6]. For the sake of simplicity the subinterleavers of these streams are omitted as they do not influence the results for the channel models considered in this paper.

For a given number l_{bl} of data bits $\underline{x}$ a block of m encoded bits $\underline{y}$ is selected for transmission resulting in a code rate $r = \frac{l_{\text{bl}}}{m}$. The size m of the block of encoded bits $\underline{y}$ is determined by the scheduler according to the user's instantaneous channel quality, maximum delay, target BER and the current load of the radio cell. Thereby the scheduler implicitly influences the code rate r of the user. The LTE *Hybrid Automatic Repeat-reQuest* (HARQ) scheme allows for up to four transmissions of different combinations of systematic and parity bits, the so-called *redundancy versions*. Obviously, each retransmission of a code block implicitly results in a decrease of the effective code rate and directly leads to losses in throughput and latency. For details of the rate

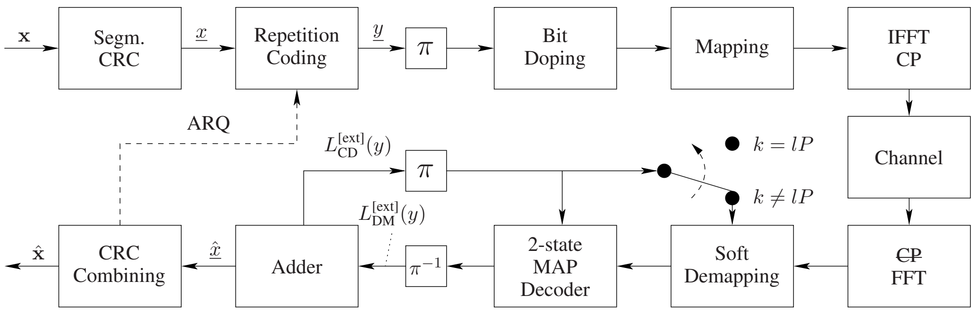

Fig. 2. Physical Layer of the alternative approach.

matching algorithm the reader is referred to [2].

The bits $\underline{y}$ selected for transmission are grouped to vectors of I bits with $I \in \{2, 4, 6\}$ which then are assigned to complex modulation symbols from a set of signal constellation symbols (SCS), i.e. QPSK, 16QAM, or 64QAM. The employed bit mapping rule for all SCS is the well-known Gray mapping. The resulting complex symbols are assigned to *resource elements* (RE), i.e., the elements of the time-frequency-grid of OFDM modulation with a bandwidth dependent number of subcarriers. OFDM modulation is realized using an Inverse Fast Fourier Transform (IFFT). Finally, a cyclic prefix (CP) is added and the transmit signal of averaged unit power and symbol energy E_S is transmitted over a channel to the receiver. Two different channel models parametrized in Sec. III are employed in both systems.

On the receiving side the CP is removed and OFDM demodulation is performed employing the Fast Fourier Transform (FFT). The demodulated complex symbols are fed to a soft demapper (SDM) which delivers reliability information in form of *log-likelihood ratios* (LLR). The LLRs $L(y)$ are then passed to a parallel turbo decoding structure consisting of two soft input soft output (SISO) channel decoders (CD) using the LogMAP algorithm [7] for soft channel decoding. After a fixed number of decoding iterations $n_{\text{it}}^{[\text{LTE}]}$ the sequence $\hat{\underline{x}}$ of data bits of each data frame is estimated from the resulting LLRs and the CRC is evaluated. In case of a frame error a retransmission is requested and combined with the already received data. Finally, the estimated data bit stream $\hat{\mathbf{x}}$ is reconstructed.

B. Considered BICM-ID scheme

To provide a fair comparison to the physical layer of UMTS LTE, the considered BICM-ID system features a similar transceiver structure sketched in Fig. 2. The binary input bit stream $\mathbf{x}$ is segmented into data frames which are then protected by a 24 bit CRC resulting in data frames $\underline{x}$ of size l_bl. Instead of transmitting combinations of systematic and parity bits from a rate-$\frac{1}{3}$ turbo coder as given in UMTS LTE, in our approach we simply repeat data bits at the same rate for channel coding. After repetition coding the coded frames $\underline{y}$ are interleaved by an S-random interleaver and fed to the bit doping [4], [5]. This is a simple rate-1 memory-1 recursive convolutional code which periodically replaces single bits of the interleaved block $\underline{y}$ with coded bits at a period length P, the so-called *doping period*. The significant influence of this bit doping will be discussed in Sec. IV-A.

As opposed to the Gray mapped constellation sets of UMTS LTE, we employ constellations with mappings that are optimized for BICM-ID, i.e. QPSK and 64QAM with Anti-Gray mapping [8] and 16QAM with *Maximum Squared Euclidian Weight* (MSEW) mapping [9]. The complex symbols are then mapped to the REs of an OFDM modulator with a CP equal to UMTS LTE forming a complex base band signal with averaged unit power and energy E_S per symbol.

After transmission over the channel and OFDM demodulation the complex symbols are soft demapped resulting in LLRs which are fed to a 2-state MAP decoder to revert the bit doping process. Deinterleaving is performed and the resulting LLRs $L_{\text{DM}}^{[\text{ext}]}(y)$ are fed to an adder that generates extrinsic information $L_{\text{CD}}^{[\text{ext}]}(y)$ [10]. This extrinsic information is then interleaved and fed back to the 2-state MAP decoder and to the soft demapper. The extrinsic information on the doped bits is set to zero, i.e., the bits at time instances $k = l \cdot P$ with doping period P and $l \in \mathbb{N}$. After a fixed number of iterations $n_{\text{it}}^{[\text{REP}]}$ an estimate of the data frame $\hat{\underline{x}}$ is passed to the CRC where in case of failure up to 3 retransmissions can be requested. Finally, the received data frames are combined to the output data stream $\hat{\mathbf{x}}$.

III. Simulation Parameters and Results

The same simulation parameters have been chosen for both systems for a fair comparison. Since the data frame size is known to have a significant effect on the performance of iterative decoding, the maximum data frame size (transport block size) of $l_\text{bl} = 6144$ is chosen as given in the UMTS LTE standard. Two effective code rates are selected: For $r = \frac{1}{3}$ the complete buffer is transmitted in the LTE case, while for BICM-ID the data frame is repeated twice resulting in the same code block length. Accordingly,

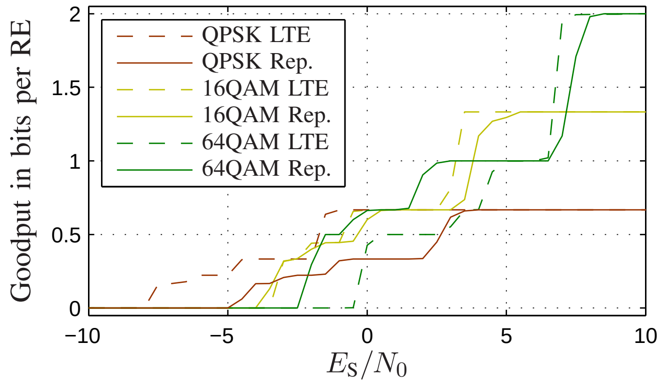

Fig. 3. Goodput per RE for code rate $r = \frac{1}{3}$ and CAWGN, $n_{\text{it}}^{[\text{REP}]} = 20$.

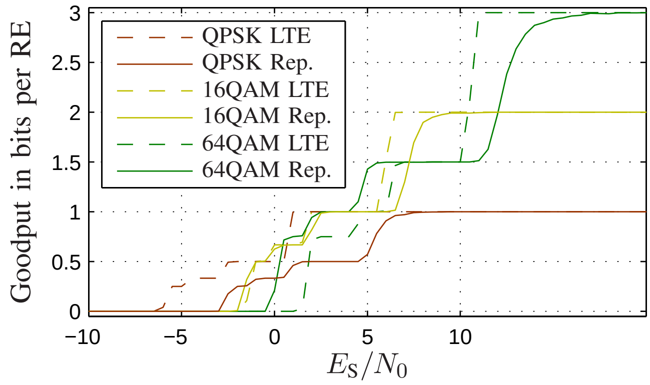

Fig. 4. Goodput per RE for code rate $r = \frac{1}{2}$ and CAWGN, $n_{\text{it}}^{[\text{REP}]} = 20$.

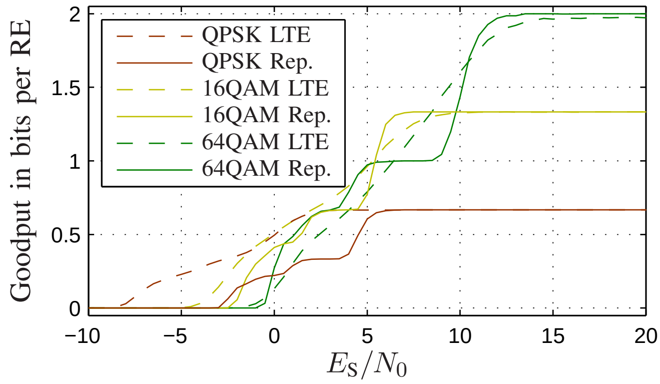

Fig. 5. Goodput per RE for code rate $r = \frac{1}{3}$ and ISI channel, $n_{\text{it}}^{[\text{REP}]} = 20$.

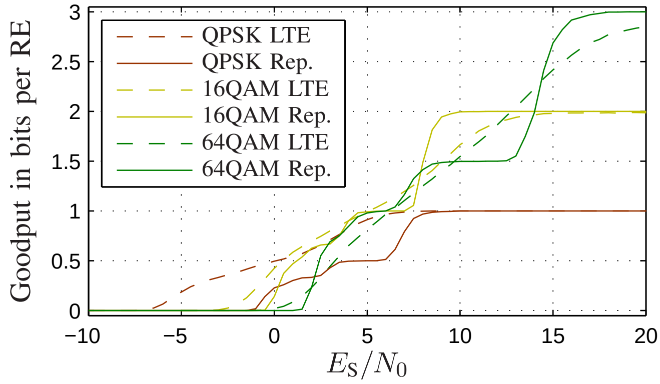

Fig. 6. Goodput per RE for code rate $r = \frac{1}{2}$ and ISI channel, $n_{\text{it}}^{[\text{REP}]} = 20$.

for $r = \frac{1}{2}$ the buffer of the LTE transmitter is punctured in compliance with the LTE standard, while the data is repeated only once for BICM-ID. A maximum number of 4 transmissions (3 retransmissions) per code block is allowed, each retransmission reducing the local effective code rate to $r_{\text{eff}} = \frac{r}{n_{\text{T}}}$ with $n_{\text{T}} \in \{1, 2, 3, 4\}$ representing the number of transmissions. Two channel models are used for evaluation. We start with a Complex Additive White Gaussian Noise (CAWGN) channel with zero mean and one-sided noise power $N_0/2$. Furthermore, we use an uncorrelated time-varying frequency-selective inter-symbol interference (ISI) channel with 4 independent Rayleigh fading taps and CAWGN. The average attenuation $\mathbf{h}$ of the channel taps is arbitrarily chosen as $\mathbf{h} \sim [1.0, 0.0, 0.5, 0.2, 0.1]$, where each tap is considered constant for the duration of one OFDM symbol. The influence of channel estimation errors at the receiver is considered to be negligible, i.e., the received signal is perfectly equalized. The LTE decoder performs $n_{\text{it}}^{[\text{LTE}]} = 10$ Turbo decoding iterations, while the BICM-ID system uses $n_{\text{it}}^{[\text{REP}]} = 20$ demodulation and decoding iterations. Both numbers have been observed to lead to convergence. Performance is measured as goodput per resource element (= channel use), i.e., as average number of correctly decoded data bits per RE, where the decision of correct or incorrect decoding is based on the CRCs of the data frames $\hat{\underline{x}}$ after retransmissions.

Figures 3 and 4 depict the goodput in bits per RE of both systems achieved in a CAWGN environment with initial code rate $r = \frac{1}{3}$ and $r = \frac{1}{2}$, respectively. The plateaus of each curve describe the converged states for a certain number of (re)transmissions. To give an example: With 64QAM, $I = 6$ bits are transmitted per RE which – with a code rate $r = \frac{1}{3}$ and $n_{\text{T}} = 1$ transmission – leads to a goodput of 2 bits per RE if the bits are correctly decoded (cf. Fig. 3). In case of retransmissions ($n_{\text{T}} \in \{2, 3, 4\}$)

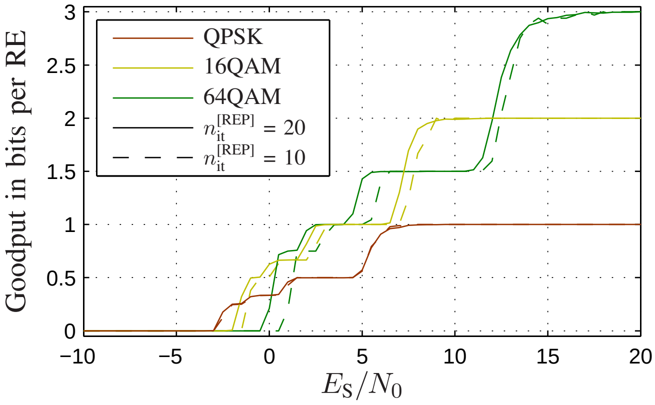

Fig. 7. Performance comparison for different $n_{\mathrm{it}}^{[\mathrm{REP}]}$ of the proposed BICM-ID system for code rate $r = \frac{1}{2}$ and CAWGN.

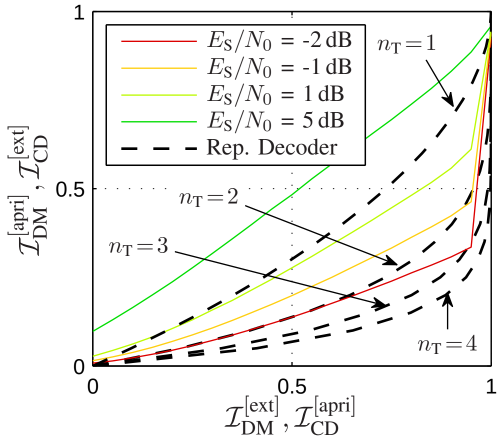

Fig. 8. EXIT Chart of proposed BICM-ID system for code rate $r = \frac{1}{3}$ and 16QAM.

the effective code rate and hence the goodput decreases with each retransmission, reaching zero when the data cannot be correctly decoded after $n_{\mathrm{T}} = 4$ transmissions in adverse channel conditions. It can be seen that for QPSK the proposed BICM-ID scheme is outperformed by standard LTE by up to 3 dB. For 16QAM, however, the performance loss is less than 1 dB and for 64QAM using $n_{\mathrm{T}} > 1$ transmissions the proposed scheme even partially outperforms standard LTE despite its lower receiver complexity.

Figures 5 and 6 depict the achieved goodput per RE in case of the Rayleigh fading channel for both employed code rates $r = \frac{1}{3}$ and $r = \frac{1}{2}$, respectively. Surprisingly, the goodput of the BICM-ID approach does not only show the plateaus observed already in Fig. 3 more distinctly, it also performs equally well as or even better than LTE for 16QAM and 64QAM.

The goodput in Fig. 7 provides a notion of the influence of the number of iterations $n_{\mathrm{it}}^{[\mathrm{REP}]}$ executed in the proposed BICM-ID receiver. It can be seen that decreasing the number of iterations in the BICM-ID system to $n_{\mathrm{it}}^{[\mathrm{REP}]} = n_{\mathrm{it}}^{[\mathrm{LTE}]} = 10$ leads to a performance degradation of 0.5 to 1.0 dB.

IV. Discussion

To discuss the findings of the previous section we first illustrate the iterative behavior of the BICM-ID system using *EXtrinsic Information Transfer* (EXIT) charts [11] followed by a brief sketch of the computational receiver complexity.

A. EXIT Analysis

EXIT charts are a well-known tool for predicting the convergence behavior of iterative systems such as BICM-ID. They depict the amount of extrinsic information $\mathcal{I}^{[\mathrm{ext}]}$ a certain receiver component can obtain for a certain amount of given a priori information $\mathcal{I}^{[\mathrm{apri}]}$ as EXIT characteristic. In case of BICM-ID, where the extrinsic information obtained by the SDM serves as a priori input for the channel decoder ($\mathcal{I}_{\mathrm{DM}}^{[\mathrm{ext}]} = f(L_{\mathrm{DM}}^{[\mathrm{ext}]}) = \mathcal{I}_{\mathrm{CD}}^{[\mathrm{apri}]}$) and vice versa ($\mathcal{I}_{\mathrm{CD}}^{[\mathrm{ext}]} = f(L_{\mathrm{CD}}^{[\mathrm{ext}]}) = \mathcal{I}_{\mathrm{DM}}^{[\mathrm{apri}]}$) an iterative gain can be obtained if a tunnel exists between the characteristics of the SDM and the channel decoder. For a more detailed description of EXIT charts for BICM-ID the reader is referred to [11].

Figure 8 depicts an EXIT chart for the BICM-ID system with rate-$\frac{1}{3}$ coding and CAWGN for 16QAM. The dashed black lines correspond to the EXIT characteristic of the repetition decoder, i.e., the adder (cf. Fig. 2), for n_{T} transmissions with $n_{\mathrm{T}} \in \{1, 2, 3, 4\}$, while the solid colored curves represent the SDM characteristics for different channel qualities including bit doping. The effect of bit doping is eye-catching: While the slope of the SDM characteristics is quite moderate for low and medium amounts of a priori information it is highly increased for high amounts of fed back a priori information, thus heavily bending the SDM characteristic toward high amounts of extrinsic information.

The figure reflects the performance of the BICM-ID system depicted in Fig. 3: The first plateau for 16QAM (yellow line in Fig. 3) is reached at $E_{\mathrm{S}}/N_0 \approx$ -2 dB, when a tunnel opens in Fig. 8 between the decoder characteristic for the 4th transmission and the SDM characteristic at -2 dB (red solid line) the same holds for the other plateaus starting at channel qualities of -1 dB, 1 dB, and 5 dB, respectively. For all these channel qualities a decoding tunnel exists in the EXIT chart in Fig. 8 between the decoder characteristics of the 3rd, 2nd, and 1st transmission and the SDM characteristic of the corresponding channel quality.

B. Algorithmic Complexity

The complexity is evaluated for the receiver, where the major part of the complexity reduction is achieved. For evaluating the logMAP algorithm complexity [7] we look at the number of additions (ADD) and so-called max*-operations executed per data bit and iteration. max*-operations are used to add probabilities in the logarithmic domain and consist of three operations: a max-operation, a table look-up and an addition. Both numbers depend on the code rate $r^{[\mathrm{cc}]}$ of the constituent code and on the number of trellis states S. The number of ADD operations N_{ADD} and max*-operations $N_{\max*}$ are given as:

$$N_{\mathrm{ADD}} = 8S + \frac{1}{r^{[\mathrm{cc}]}} 2^{\frac{1}{r^{[\mathrm{cc}]}}}, \qquad N_{\max*} = 4S. \quad (1)$$

In the LTE receiver two logMAP algorithms with $S^{[\mathrm{LTE}]} = 8$ states and $r^{[\mathrm{cc,LTE}]} = \frac{1}{2}$ are executed, while the BICM-ID system with repetition coding [REP] uses code rate $r^{[\mathrm{cc,REP}]} = 1$ for convolutional coding and a trellis with $S^{[\mathrm{REP}]} = 2$ states. However, while LTE executes the logMAP algorithm on the data frame of length l_{bl}, the logMAP decoder of BICM-ID receiver uses the coded bit frames as input. Their length is determined by the code rate of the complete system and given by $\frac{l_{\mathrm{bl}}}{r}$. Additionally, LTE and BICM-ID receiver run different numbers of Turbo iterations $n_{\mathrm{it}}^{[\mathrm{LTE}]}$ and $n_{\mathrm{it}}^{[\mathrm{REP}]}$, respectively. Therefore, considering the same data frame size l_{bl} for both systems, the ratios of the two performance measures from (1) of the two considered systems are given by:

$$\frac{N_{\mathrm{ADD}}^{[\mathrm{REP}]}}{N_{\mathrm{ADD}}^{[\mathrm{LTE}]}} = \frac{N_{\max*}^{[\mathrm{REP}]}}{N_{\max*}^{[\mathrm{LTE}]}} = \frac{n_{\mathrm{it}}^{[\mathrm{REP}]}}{8 r n_{\mathrm{it}}^{[\mathrm{LTE}]}}. \quad (2)$$

For the scenario depicted in Figs. 4 and 6 with $r = \frac{1}{2}$, $n_{\mathrm{it}}^{[\mathrm{REP}]} = 20$, and $n_{\mathrm{it}}^{[\mathrm{LTE}]} = 10$ the number of additions and max*-operations in the logMAP decoder can accordingly be reduced by 50 %.

Additionally, the BICM-ID receiver uses a simple adder for decoding, executing $\frac{1}{r} - 1$ additions for the repetition rate (= coding rate) r per bit and iteration. The soft demodulator has to calculate extrinsic information for each coded bit in each iteration, which would lead to an additional number of $2^I - 2$ additions with $I \in \{2, 4, 6\}$ representing the size of the set of signal constellation symbols. However, the complexity of the SDM can be reduced vastly by reducing the number of transition probabilities considering only the nearest neighbors in a given signal constellation. This modification only marginally decreases the performance of the SDM. A further complexity reduction for both systems is obviously obtained when a proper stopping criterion for the iterative processes is used, e.g., based on the CRC, instead of a fixed number of iterations.

V. Conclusion

In this contribution we have considered a BICM-ID system with repetition coding and compared its performance to that of an LTE transceiver. For CAWGN and ISI environments both systems obtain a comparable performance considering the goodput, especially for higher order modulations (16QAM, 64QAM). However, the BICM-ID system exhibits a significant reduction of complexity for the logMAP decoder reducing additions and max*-operations by up to 50 % for an exemplary given case.

Acknowledgment

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References

[1] 3GPP TS 36.211, "Evolved Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation," Version 8.2.0, 3GPP Technical Specification, 2008.

[2] 3GPP TS 36.212, "Evolved Terrestrial Radio Access (E-UTRA); Multiplexing and Channel Coding," Version 8.2.0, 3GPP Technical Specification, 2008.

[3] X. Li, A. Chindapol, and J. A. Ritcey, "Bit-Interleaved Coded Modulation with Iterative Decoding and 8PSK Signalling," *IEEE Transactions on Communications*, vol. 50, no. 8, pp. 1250 – 1257, Aug. 2002.

[4] S. Pfletschinger and F. Sanzi, "Error Floor Removal for Bit-Interleaved Coded Modulation with Iterative Detection," *IEEE Transactions on Communications*, vol. 5, no. 11, pp. 3174–3181, Nov. 2006.

[5] F. Schreckenbach, *Iterative Decoding of Bit-Interleaved Coded Modulation*, Ph.D. thesis, Technische Universität München, 2007.

[6] J. Cheng, A. Nimbalker, Y. Blankenship, B. Classon, and T. Blankenship, "Analysis of Circular Buffer Rate Matching for LTE Turbo Code," in *Proceedings of IEEE Vehicular Technology Conference (VTC-Fall)*, Calgary, Canada, Sept. 2008.

[7] P. Robertson, E. Villebrun, and P. Hoeher, "A Comparison of Optimal and Sub-Optimal MAP Decoding Algorithms Operating in the Log Domain," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Seattle, USA, 1995, pp. 1009–1013.

[8] T.-W. Yu, C.-Y. Wang, C.-H. Wang, and W.-H. Sheen, "EXIT-Chart Based Labeling Design for Bit-interleaved Coded Modulation with Iterative Decoding," in *Information Theory, 2007. ISIT 2007. IEEE International Symposium on*, Nice, June 2007, pp. 56–60.

[9] J. Tan and G. L. Stöber, "Analysis and Design of Interleaver Mappings for Iteratively Decoded BICM," *International Conference on Communications (ICC)*, vol. 3, pp. 1403–1407, Apr./May 2002.

[10] D. Divsalar and F. Pollara, "Hybrid Concatenated Codes and Iterative Decoding," Aug. 1997.

[11] S. ten Brink, "Designing Iterative Decoding Schemes with the Extrinsic Information Transfer Chart," *AEÜ Int. J. Electron. Commun.*, pp. 389 – 398, Nov. 2000.