Turbo Coded Modulation for High-Throughput TDMA Systems

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Abstract

A high level modulation (8-PSK) was introduced in the evolution of GSM or EDGE. Using this modulation the maximum data throughput which can be achieved in the EGPRS protocol is 473.6kbps. For the next generation of mobile communications there is a demand for systems capable of achieving even higher data rates (1-10Mbps). In this paper we proceed to the application of 16/64-QAM modulation, combined with strong coding schemes like turbo codes in order to achieve even higher throughput. The channels considered here are the AWGN and the one-path Rayleigh. Besides the evaluation of the system (through simulations), extensive comparisons with the same system employing convolutional codes of equivalent complexity have been performed.

1. Introduction

It is well known that Turbo codes [1], achieve remarkable performance with medium and large information blocks. In mobile communications we are limited to transmit a few hundred symbols over the air. Therefore for constellations like QPSK or 8-PSK (which are used in the current TDMA systems), Turbo codes don't perform well compared to convolutional codes, because the information block size (in bits) is small.

The use of higher level modulations like 16/64-QAM can offer a substantial increase in the block size while keeping the symbol rate constant. Therefore Turbo-coded modulation can benefit from that as compared to convolutional-coded modulation schemes.

Furthermore, we combine multiple slots (within a TDMA frame) when it is possible. This translates to a large block (and consequently channel interleaver) size which is essential for the Turbo codes to achieve good performance in correlated fading channels.

In this paper we use punctured Turbo codes, derived from a rate 1/3 parallel-concatenated convolutional code (PCCC), of rates 1/2 through 5/6. They combined through a pseudo-random bit interleaver with 16 and 64 gray coded QAM constellations, [2],[3]. The system's performance is evaluated using simulations.

An extensive comparison in terms of complexity and performance is also shown. The counter system employs punctured convolutional codes instead of Turbo codes.

The organization of the paper is as follows. In Section 2 we present the slot structure and the multislot concept. In Section 3 a brief description of the Turbo coded modulation scheme is given, and in Sections 4 and 5 we present the system's performance for one and four slots respectively. Section 6 deals with the complexity versus performance, and we conclude in Section 7.

2. Slot structure and multislot concept

We have kept about the same frame structure as in the EGPRS [4], for reference purposes, although in this work we assume perfect channel state information (so we don't need tail and training symbols). We assume each radio block (RB) consists of 464 coded data symbols and these symbols are divided among 4 slots of 116 symbols each. Figure 1 shows the slot structure for the single slot case, i.e. the user occupies one slot per TDMA frame (or just frame). Note that both headers and user data are included in the DS (see Fig. 1), but in this work we handle them both as the data of interest (performance-wise).

Currently in the EGPRS more than one slot (theoretically all 8 slots in a frame) can be assigned to one mobile terminal. The use of multiple slots within a frame increases the throughput (as well the decoding complexity) without increasing the delay. In the EGPRS standard each

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radio block is encoded separately regardless of the number of slots (in a frame) occupied by the user.

Turbo codes can benefit from the multislot case (as compared to the single slot) if we encode a big block consisting of all the radio blocks (equal to the number of the slots per frame). Therefore by increasing the throughput, which increases also the channel interleaver's size, we hope to increase as well the performance of the system. In the four-slot case we will present later, each user uses every other slot of the frame (see Fig. 1).

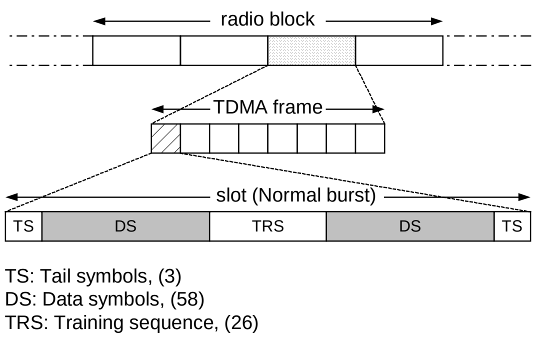

Figure 1. Single slot structure.

3. System overview

The system model considered in this paper is depicted in Fig. 2, [2],[3]. The Turbo code is a PCCC with identical constituent codes (cc) combined through an S random interleaver [5] (see Tables 1 and 2). The generator polynomials of the cc's are $[13_8,15_8]$ with 13_8 being the feedback polynomial.

Using parity bit puncturing we achieve different throughputs η (bits/symbol) along with the M-ary ($M=2^m$) gray-coded QAM modulation, i.e. the overall code rate is η/m. The block size is $N=\eta \cdot K \cdot 464$, where K is the number of slots per frame. After the puncturing, the bits are interleaved with a random-like channel interleaver and following the formulation of the slot, they mapped to 2^m gray coded QAM symbols.

For the fading channel we have used the Jakes' time domain Rayleigh model as described in [6]. Perfect channel state information is assumed (i.e. known noise variance and fading amplitude), and a bit-soft demodulator is used. By SNR_b we denote the signal-to-noise ratio per information bit. The carrier frequency is 900MHz and the symbol period 3.69μs. The maximum information data rate employing a rate 5/6 64-QAM is approximately 789kbps.

Finally the decoding is performed using a MAP Turbo decoder with four iterations (unless otherwise stated) [7]. From the study of Viterbi [8], we can figure that the processing load of our decoder (with four iterations) is approximately no more than that of a 256-state rate 1/2 Viterbi algorithm (VA).

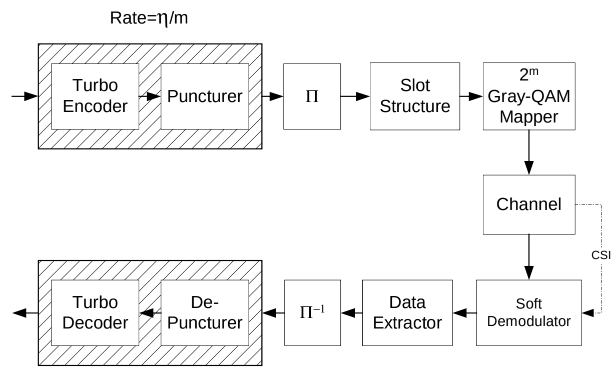

Figure 2. System model.

4. Single-slot Performance

In the Figures 3-7, the performance (block error rate, BLER) of our system for a single-slot case is given for different channels. In the legends of the graphs the systems are denoted by their overall code rate, i.e. η/m.

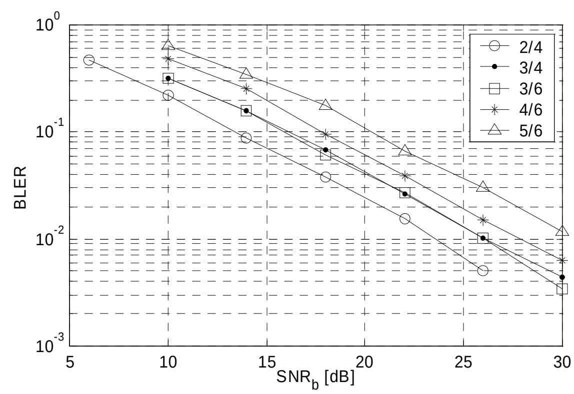

Figure 3. Performance over the 3km/hr fading channel.

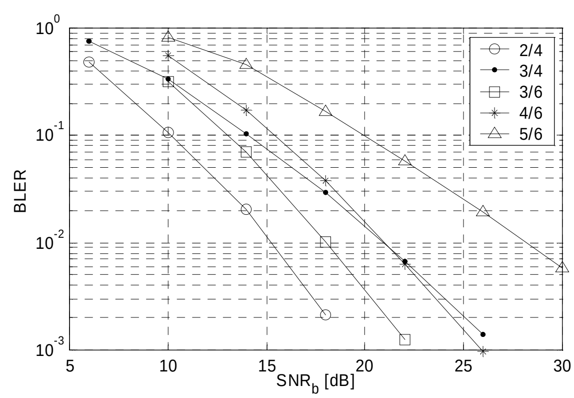

Figure 4. Performance over the 50km/hr fading channel.

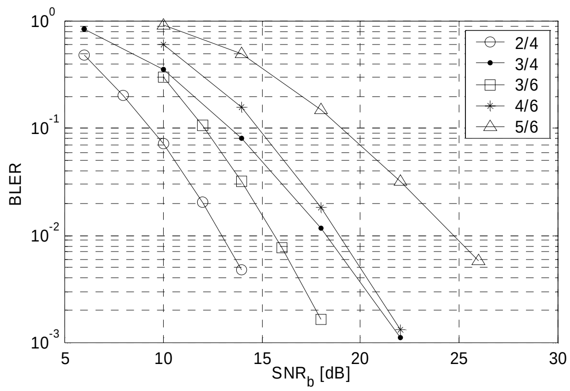

Figure 5. Performance over the 250km/hr fading channel.

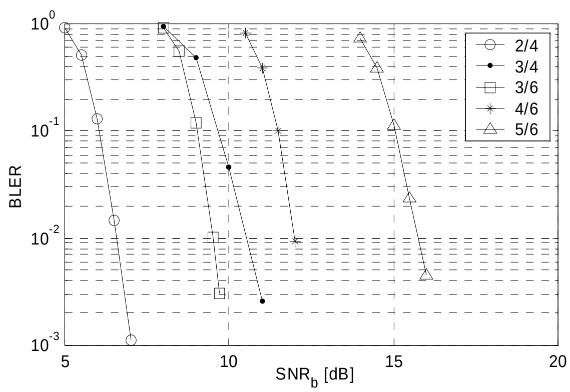

Figure 6. Performance over the indpendent fading channel.

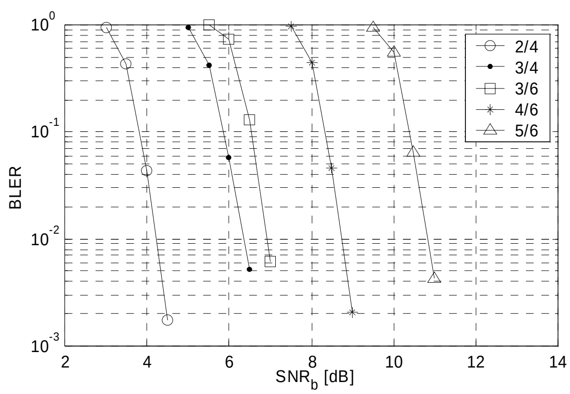

Figure 7. Performance over the AWGN channel.

Due to the limited paper space, we present some of the results in tables. In Table 1 we have the SNR_b (in dB) required to achieve 10^{-3} bit error rate (BER) for each system. For the slow fading channel (3km/hr) we see that the different coding schemes have about the same diversity (slope), which is not the case for the faster channels of 50km/hr and 250km/hr. We will see later that even by doubling the complexity of the coding scheme (i.e. doubling the number of iterations to eight), we don't get any significant coding gain. This is because of the large fade duration in the slow fading channel as opposed to the fast fading channels. In the fast fading channels the better the code, the steeper the slope of the performance curve.

Note that the slope of the 3/6 system is steeper than that of the 3/4 system in all fading channels except the 3km/hr fading channel. This is something expected (assuming the channel coding is enough powerful) i.e. see Ungerboeck's original TCM work, [9]. If we compare Figures 6 and 7 (see also Table 1), we see that the 3/6 is better from the 3/4 in the independent fading channel, than in the AWGN and vice versa. This may be explained by the fact that we assume perfect knowledge of the channel, so in the fading compensation we effectively multiply the noise variance. Since the intersection point (between the performance of the 3/4 and 3/6 systems) occurs in high SNR_b, we have the 3/6 to be better in fading channels.

Table 1. 10^{-3} BER of the various systems.

System/ Channel	2/4 S=15	3/4 S=18	3/6 S=18	4/6 S=22	5/6 S=23
3km/hr	25.3	26.5	27.8	28.8	29.8
50km/hr	15.4	19.2	18.2	20.3	25.4
250km/hr	12.9	16.8	15.3	17.9	22.3
Indep. Fading	6.2	9.6	9.0	11.4	14.9
AWGN	3.9	5.8	6.5	8.2	10.3

5. Four-slot Performance

Tables 2 and 3 contain the required SNR_b (in dB) to achieve 10^{-2} BLER and 10^{-3} BER (respectively) for each system and for the four-slot case (K=4).

Table 2. 10^{-2} BLER of the various systems.

System/ Channel	2/4	3/4	3/6	4/6	5/6
3km/hr	23.4	25.8	26.4	27.9	30.7
50km/hr	15.0	19.2	18.0	20.8	25.0
250km/hr	10.0	14.5	13.5	16.1	20.5
Indep. Fading	6.2	10.0	9.3	11.7	15.3
AWGN	4.0	6.1	6.8	8.6	10.6

We can see that the improvement in performance due to the increased block length is bigger for the weak coding schemes as well as for the fast fading channels as expected. In the slow channel the improvement is negligible. In Figure 8 we compare the performance of the rate 3/4 system with one and four slot configurations for some channels. In the independent fading channel the gain we see is due to the Turbo coding solely, while in the other channels, the gain is also due to the increased size of the channel interleaver.

Table 3. 10^{-3} BER of the various systems.

System/ Channel	2/4 S=28	3/4 S=30	3/6 S=30	4/6 S=28	5/6 S=26
3km/hr	25.3	26.0	28.0	28.7	29.8
50km/hr	15.0	18.4	18.0	20.2	23.0
250km/hr	9.5	13.2	12.9	15.1	18.6
Indep. Fading	5.8	9.2	8.8	11.1	14.5
AWGN	3.6	5.6	6.3	8.1	10.1

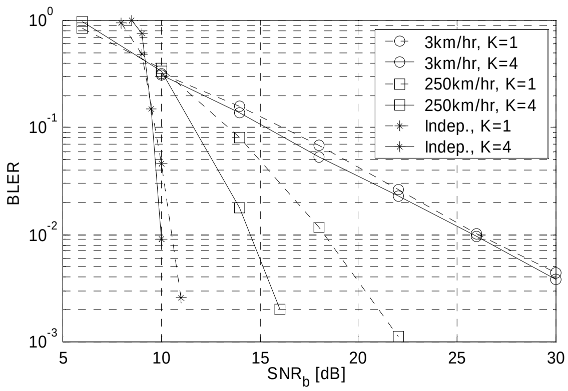

Figure 8. Single-slot vs. four-slot performance comparison for the rate 3/4 16-QAM system.

6. Performance vs. Complexity

In this Section we will try to evaluate how good are the Turbo Codes (TC) as compared to Convolutional Codes (CC) of equal complexity, when both used as the coding part of our system. Note that when we use CC we modify only the shadowed (co-decoding) part (see Fig. 2) of our system. The complexity (by complexity we refer only to the processing load) of our Turbo decoding scheme is approximately no more than that of a 64-state VA (of a rate 1/2 CC) per iteration, [8].

Here we have used only rate 3/4 coding schemes with block length corresponding to one slot per frame (K=1). We compare the TC employing four iterations with a 256-state CC (punctured from rate 1/4, Table IV, [10]). Likewise we compare the TC employing eight iterations with a 512-state CC (punctured from rate 1/2, Table VIII, [11]).

In Figure 9 we compare the TC (4 iterations) vs. the CC (256 states) for different fading channels, where the superiority of the Turbo coding scheme is obvious. Both BLER and BER curves are shown (Figures 9a and 9b correspondingly). In Figure 10 we see that by increasing the complexity of the system, there is no significant improvement in the performance especially in the slow-fading channel. We could say that in the fading channels the most critical parameter for the improvement of the performance of our scheme is the increased block length (compare to Fig. 8) and not the number of iterations (see Fig. 10).

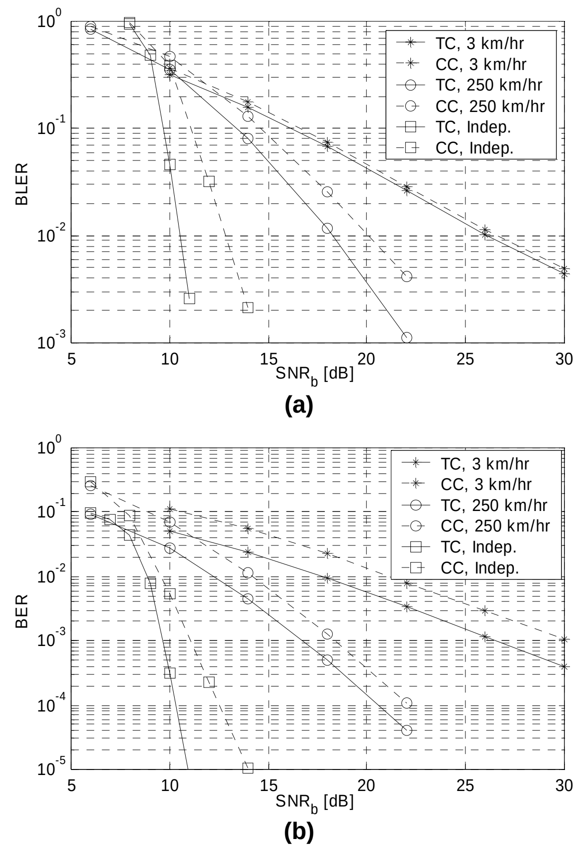

Figure 9. Performance comparison of Turbo vs. Convolutional coded modulation (Rate 3/4 16-QAM), (1).

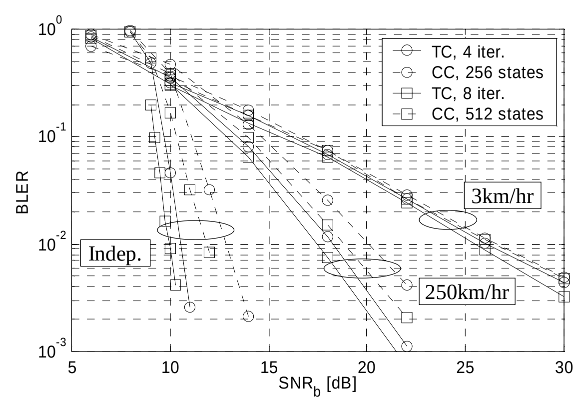

Figure 10. Performance comparison of Turbo vs. Convolutional coded modulation (Rate 3/4 16-QAM), (2).

The complexity of the Turbo coding scheme can be reduced further by employing some stopping rules to the iterative decoding process, without affecting significantly the performance, as has been shown in [12]. In this paper we are using "perfect" CRC, i.e. we stop the iterations when the block has been decoded correctly. When the number of iterations is small (as in this work) we have found that the performance (of our system) is identical if we use perfect CRC or fixed number of iterations. In Figure 11 we see that even in 8 iterations (fixed) we don't have any significant drift from the "optimum" perfect CRC curve. However in [12] they have shown that performance very close to perfect CRC is achievable using some decoding stopping rules, for both BER and BLER. Furthermore in the range of interest (10^{-1}-10^{-2} BLER) a typical CRC can achieve the same performance as the perfect one [13],[12].

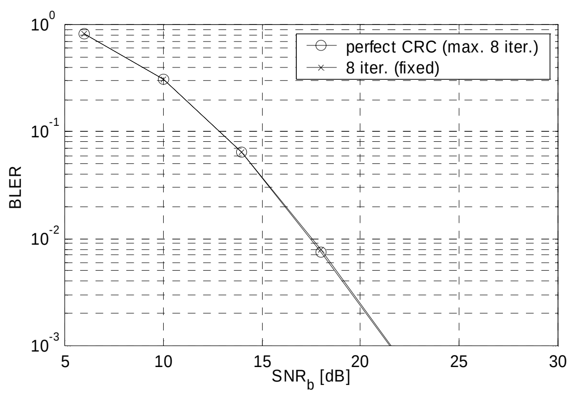

Figure 11. Turbo Decoding Stopping Rule for the rate 3/4 16-QAM over the 250km/hr fading channel.

7. Conclusions

In this paper we studied through simulations a turbo coded modulation scheme applied to a TDMA system (EGPRS-like) for various single path channels. It seems that the most important parameter that determines the performance of the system in the fading channels is the block size and not the complexity of the code (i.e. the number of decoding iterations). This is true especially in slow fading channels.

From the comparisons to convolutional-coded schemes, it seems that our system is performing much better with equal or less complexity. An important advantage of the Turbo schemes is that by employing some stop (iterative) decoding rules, one can reduce dramatically the decoding complexity.

Some open items are the performance comparison with suboptimal turbo decoding algorithms, and the effect of the channel estimation errors in a multipath fading channel. Also the effects of receiver impairments, like phase noise for example, should be taken into account especially for the 64-QAM schemes.

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