TTCM-OFDM over Dispersive Fading Channels

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Abstract—**In this contribution Orthogonal Frequency Division Multiplexing (OFDM) is proposed as a convenient digital modulation scheme to transmit data encoded by means of Turbo Trellis Coded Modulation (TTCM). The resulting transmission system is described and the advantages of using OFDM to transmit TTCM encoded data are highlighted. The system is investigated by means of simulations in order to assess its performance over dispersive deterministic channels and over dispersive Rayleigh fading channels. As a benchmarker, a system having a similar computational complexity, but employing classical Trellis Coded Modulation (TCM) to encode the data is also investigated.**

I. Introduction

Following the invention of Turbo Codes (TC) [1], a number of techniques have been proposed in the literature, which aim at retaining the powerful error correction capabilities of these codes, while achieving a high bandwidth efficiency. A survey of the proposed solutions can be found in [2]. Amongst these techniques, a promising one is Turbo Trellis Coded Modulation (TTCM) [3], which elegantly incorporates the turbo concept into the well known Trellis Coded Modulation (TCM) [4] scheme. TTCM has proven powerful over Gaussian channels [3], however, its performance is not well documented over frequency selective fading channels. In this paper we assess the performance of TTCM over such channels.

When the channel is dispersive, either channel equalization must be incorporated into the system or the channel has to be rendered non-dispersive with the aid of Orthogonal Frequency Division Multiplexing (OFDM) [5]. We opted for the latter option in this contribution, since then the results are independent of the specific equaliser used and hence become more widely applicable.

The paper is organized as follows. In section II we briefly describe the TTCM-OFDM system, highligthing its major features. In section III we introduce the investigated channels and the system used as a benchmarker. In section IV we present and discuss our simulation results, while Section V offers our conclusions.

II. The TTCM-OFDM transmission system

The schematic of the TTCM-OFDM transmission system is shown in Fig. 1. A TTCM encoder [3], constituted by two TCM encoders [4] operating in parallel, with an iterleaver between them, encodes a block of N_i input symbols u_k belonging to an alphabet $\{0, 1, ..., M-1\}$. The selector at the encoder's output alternately selects symbols from the upper and lower encoder. The resulting block of N_i output symbols x_k, belonging to an extended $2 \cdot M$-point constellation, is passed to the OFDM modulator by means of the symbol-based channel interleaver. More specifically, in this contribution 2 bit/symbol useful information will be mapped to 3 bit/symbol 8-level Phase Shift Keying (8PSK) constellations as well as 3 bit/symbol useful information will be conveyed using a 16-level Quadrature Amplitude Modulation (16QAM) constellation [5]. The channel interleaver has the same dimension as the TTCM interleaver. The number of carriers used by the OFDM modulator is N, where N is not necessarily equal to the TTCM block dimension N_i. The OFDM signal is transmitted through the communications channel and the received data signal is demodulated by the OFDM receiver, which passes a set of impaired received symbols y_k to the channel deinterleaver and then to the TTCM decoder complex of Fig. 1. In the decoder, two Maximum-A-Posteriori (MAP) decoders [3], [6] operate iteratively in parallel, separated by the interleaver, and the soft-output of one of the two is used as an additional input to the other, completing the turbo decoder. Both the channel and the TTCM interleavers are random interleavers. The TTCM interleaver is odd-even separated [3].

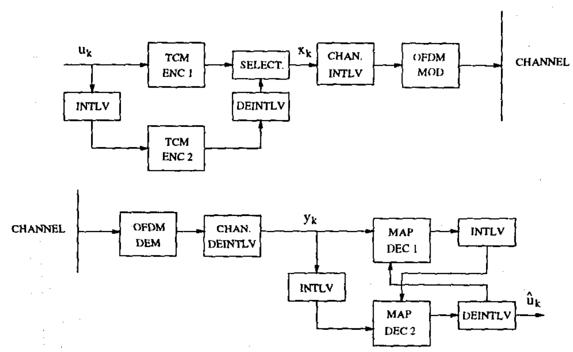

Fig. 1. TTCM-OFDM schematic

The main advantage of using OFDM for transmitting data over time dispersive channels is that the output symbols of the OFDM receiver are free of Inter-Symbol-Interference (ISI). Indeed, provided that the OFDM preamble [5] is longer than the channel impulse response, the received symbols are given by $y_k = c_k \cdot x_k + n_k$ for $k = 0, \ldots, N_i - 1$, where c_k is the value of the complex frequency-domain channel transfer function at the subcarrier conveying the $k-th$ encoded symbol and n_k is the complex Additive White Gaussian Noise (AWGN).

Due to the absence of ISI, the MAP algorithm can readily be modified, in order to take into account the effects of the channel. In fact, the received values y_k are used in the MAP algorithm only to evaluate the set of probabilities

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$p_{k,i} = p(y_k|x_k = s_i)$, where s_i represents all the $2M$ possible contellation points. These probabilities are needed during the decoding process and over AWGN channels these probabilities can be readily evaluated (see A3 of [3]). When the channel is frequency selective and OFDM is used to transmit the data, provided that we have a good estimate of the channel's transfer function and of the noise variance, these probabilities are given by:

$$p_{k,i} = \frac{1}{\pi\sigma^2} e^{-\frac{|y_k - c_k \cdot s_i|^2}{\sigma^2}},$$

where σ^2 is the variance of the complex AWGN. Thus, when OFDM is used, the OFDM demodulator's output can be fed directly into the TTCM decoder, realizing joint MAP equalization and decoding. We note additionally that the TTCM decoder minimises the symbol error probability by computing the A-Posteriori-Probability (APP) of the transmitted symbol, given the received sequence, i.e. by determining $p(u_k = m|y_1, y_2, ..., y_{N_i})$. If the exact APPs were found, the joint equalizer and decoder would be the optimum one, in the sense that it would minimize the associated symbol error probability. However, in practice only the approximate APPs are found, hence the resulting joint equalizer and decoder will be marginally suboptimum.

The channel interleaver of Fig. 1 assists in dispersing the clusters of severely impaired TCM/TTCM symbols mapped to the OFDM carriers, since if these carriers are dispersed, the code is more likely to recover the data transmitted on isolated impaired carriers, provided that the surrounding carriers are unimpaired. In all of our experiments the channel interleaver dimension has been fixed to be equal to the TTCM interleaver's dimension, although this is not a necessary constraint. Instead, over fading channels a higher-depth channel interleaver can be employed, in order to guarantee independent fading of each subcarrier, conveying a TCM or TTCM symbol.

III. Simulation environment

A number of parameters may be varied in a TTCM-OFDM system and their values affect the performance as well as the complexity and the throughput of the system. Amongst the most important ones are the number of bits per TCM or TTCM symbol, the choice of the TCM code, the TTCM interleaver memory, which is equal to the TTCM encoder's block dimension, the number of iterations in the decoder and the number of OFDM subcarriers. We considered four different codes proposed in [3]. The first two are the 2/3-rate memory three and memory four 8PSK codes, which again, carry two information bits and one parity bit per symbol, and the second two are the 3/4-rate memory three and memory four 16QAM codes, which carry three information bits and one parity bit per symbol. The octally represented generator polynomials of these codes are reported in Tab. I [3], [4]. As to the TTCM interleaver length and to the number of OFDM subcarriers, we note that for a convenient implementation the values of these two parameters are ideally equal. However, since it is well known that the turbo-concept is more efficient for longer interleavers, we also considered the case, where we have a TTCM block longer than the number of OFDM subcarriers. More explicitly, we focused our attention on two different situations, i.e. $N = N_i = 1024$ and $N = 512, N_i = 5000$.

	8PSK				16QAM			
Mem.	3	4	6	7	3	4	6	7
h_0	11	23	103	277	11	23	101	203
h_1	2	2	30	54	2	2	16	14
h_2	4	10	66	122	4	4	64	42
h_3	-	-	-	-	10	10	0	0

TABLE I

Generator polynomials used in the various TCM and TTCM schemes [3], [4]. The TTCM schemes had a memory of 3 or 4, while the TCM schemes used a memory of 6 or 7, in order to maintain a similar complexityfor both 8PSK and 16QAM.

In both cases the preamble of the OFDM symbol was fixed to 20 samples. Since performing more than four iterations in the turbo decoder only marginally increased the performance, we fixed the number of iterations to four.

We investigated the TTCM-OFDM system in three different transmission environments. The first environment is an AWGN channel. The second channel models a 155 Mbit/s non-line-of-sight (NLOS) dispersive indoor Wireless Asynchronous Transfer Mode (WATM) link between a stationary transmitter and receiver at a carrier frequency of $60GHz$ having a bandwidth of $200MHz$. The lowpass equivalent complex channel impulse response (CIR) of the NLOS channel is reported in Tab. II, which was derived from measurements. The resulting stylised frequency-domain transfer function is seen in Fig. 2. The third transmission channel models a mobile receiver in a bad urban environment, at a carrier frequency of 2 GHz transmitting in a bandwidth of approximately 2 MHz, and hence it is representative of a Universal Mobile Telecommunication System (UMTS) channel. The approach suggested in [5] was pursued in modelling the dispersive, Rayleigh fading wireless channel. The normalized Doppler frequency was $f_d = 10^{-5}$, which accounts for a vehicular speed of about 50 Km/h. The CIR tap magnitudes of the UMTS channel are also summarized in Tab. II, and the corresponding stylised frequency-domain transfer function is seen in Fig. 2. It can be observed that both the NLOS and the UMTS channels are severely frequency selective, but the latter is also time-variant. In our investigations we assumed perfect CIR knowledge and exact timing and frequency synchronization. Furthermore, the CIR of the UMTS channel was time-invariant during an OFDM symbol and it was updated at the commencement of a new OFDM symbol, which we referred to as symbol-invariant fading.

As a benchmarker, we also used a TCM-OFDM system. We used the same joint MAP equalizer and decoder in the TCM-OFDM system as in the TTCM-OFDM scheme. However, in the TCM-OFDM system the decoder is invoked only once per block, while in the TTCM-OFDM systems using four iterations it is invoked eight times. Since the decoding complexity is proportional to the number of encoder states - which is 2^L, where L is the code memory - for the sake of comparing systems having similar decoding complexity we used TCM codes having a higher code memory. Specifically, for the TCM-OFDM system we used TCM codes having memories of six and seven. These systems exhibit a decoding complexity similar to the TTCM-OFDM system having a memory of three and four, respectively. The TCM codes are those advocated by Ungerboeck [7], and their generator polynomials are also reported in Tab. I.

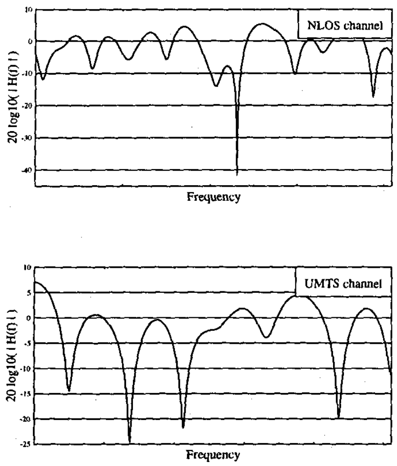

Fig. 2. Stylised plots of the frequency-domain channel transfer functions used

	NLOS		UMTS	
path delay	real	imag.	path delay	amp.
0	.23	.44	0	.70
3	-.00	.15	3	.35
4	-.05	-.59	6	.17
7	-.14	-.05	8	.11
8	-.05	.14	11	.48
9	.51	.03	13	.30
11	-.03	-.07	17	.12
14	.14	-.14		

TABLE II

IMPULSE RESPONSE AND AMPLITUDE-DELAY PROFILE OF THE CHANNELS USED

IV. SIMULATION RESULTS

In this section we present our results. *In the legends we report two numbers separated by a semi-colon. The first number is the code memory length, and if it is three or four, the system concerned is TTCM-OFDM, while if it is six or seven, the associated system is TCM-OFDM. The second number is the channel interleaver's dimension, which is equal to the TCM or TTCM encoder's block dimension. When a third number is present, it indicates the number of OFDM subcarriers. When the number of OFDM subcarriers was not indicated, then in conjunction with the 1024-symbol TCM or TTCM interleaver a 1024-carrier OFDM symbol was used, while for the 5000-symbol interleaver a 512-carrier OFDM symbol was employed.* We will present the bit error rate (BER) versus E_b/N_0 performance, where E_b/N_0 is the ratio of the transmitted energy per information bit to the noise spectral density. An OFDM preamble of 20 samples was used in all the OFDM symbols [5]. Since in the preamble no useful information is transmitted, its inclusion results in a performance degradation with respect to a system operating without it, which is 0.16 dB when 512 subcarriers are used, and 0.08 dB in conjunction with 1024 carriers.

A. AWGN channel

Fig. 3 displays the BER performance of the 8PSK TTCM- and TCM-OFDM systems over an AWGN channel. In addition to the TCM and TTCM schemes also the BER of an uncoded QPSK-OFDM system is reported. The curves for the memory three codes were already presented in [3] and - when taking into account the performance loss due to the preamble - are in close agreement with Robertson's results. The figure clearly shows the improvement yielded by TTCM over the TCM scheme, where a gain of about 1.5 dB was observed at a BER of 10^{-5}. Furthermore, it is clear that the performance of the TTCM scheme improves upon increasing the interleaver dimension. However, for low BERs the code's memory plays a more dominant role, than the interleaver. On this note, observe that at a BER of 10^{-6} TTCM having a memory of four and interleaver dimension of 1024 requires a lower transmit power, than the TTCM scheme in conjunction with a memory of three and interleaver dimension of 5000 TTCM symbols. When the TCM scheme is considered, the block dimension is not expected to improve the performance, since no turbo-interleaver is used and over AWGN channels the channel interlever does not influence the code's performance. In fact, the 5000-symbol block has slightly inferior performance in comparison to the 1024-symbol block dimension. This is due to the higher E_b/N_0 loss experienced by the 512-carrier OFDM scheme, when the preamble's effect is taken into account. The performance of the TCM scheme improves sligthly by increasing the code's memory from six to seven.

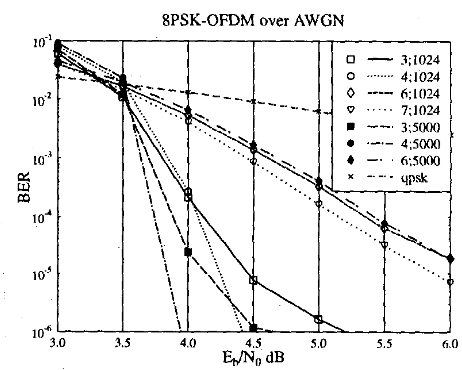

Fig. 3. Performance of the various 8PSK TCM and TTCM schemes over AWGN channels. The first number in the legend is the code memory, and if it is 3 or 4, the system concerned is TTCM-OFDM, while if it is 6 or 7, the system is TCM-OFDM. The second number is the block dimension. When a third number is present, it indicates the number of OFDM subcarriers.

Similar conclusions are valid when considering 16QAM, as seen in Fig. 4. The importance of the code memory is more pronounced in conjunction with 16QAM. Observe in Figure 4 that the memory three code experiences a BER floor - a phenomenon, well-known in the context of turbo codes - which is effectively combated by the memory four code. We note that the performance of the memory three, block length 5000 scenario is in close agreement with the corresponding results presented in [3].

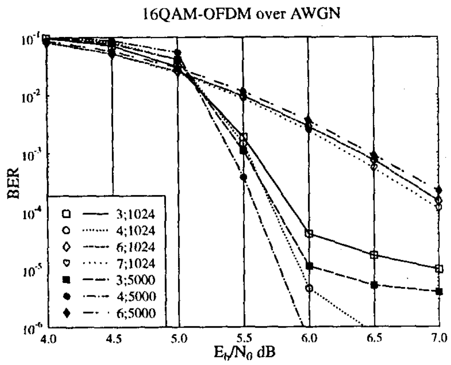

Fig. 4. Performance of the various 16QAM TCM and TTCM schemes over AWGN channels. For legends refer to Figure 3.

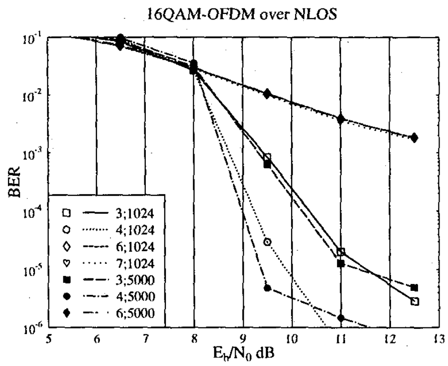

Fig. 6. Performance of the various 16QAM TCM and TTCM schemes over the NLOS channel of Table II. For legends refer to Figure 3.

B. NLOS channel

Figs. 5 and 6 report our results over the NLOS channel for 8PSK and 16QAM, respectively. Over this frequency selective channel the gain of the TTCM scheme over the TCM one is more pronounced. For example, up to five dB SNR gain can be attained at a BER of 10^{-5} for 8PSK. However, over this channel the effect of the block dimension on the performance of the TTCM scheme is less pronounced. Indeed, at low BERs it can be seen that the 1024-symbol block TTCM performs better, than the 5000-symbol block scheme for both 8PSK and 16QAM. As we will see during our further discourse, the block dimension must be increased further, in order to attain more substantial improvements. The code memory has a strong influence on the performance also over this channel, as demonstrated by the memory four codes with respect to the memory three codes, in particular at low BERs.

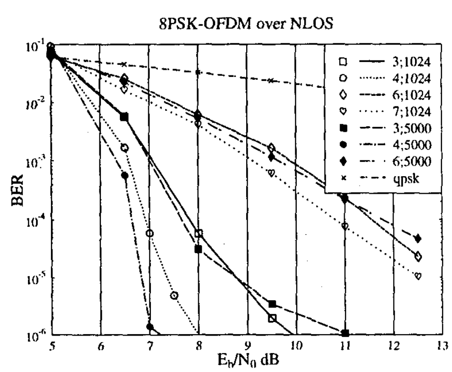

Fig. 5. Performance of the various 8PSK TCM and TTCM schemes over the NLOS channel of Table II. For legends refer to Figure 3.

Fig. 7 presents additional results for 16QAM upon increasing the number of TTCM iterations. Note that 1024 carriers were used for all the curves in this figure, in order to compare the different TTCM schemes under identical conditions. Specifically, we performed eight iterations instead of four, hence the curves are identified in the legend by the suffix .8i. It can be seen that increasing the number of iterations has no significant effect on the BER. In fact, the BER can even be slightly degraded, when performing eight iterations. Observe that in Fig. 7 we also studied the effect of a higher block dimension. It can be seen that if the block dimension is increased to 20000 symbols, then there is a clear performance improvement - as expected - when using a TTCM scheme. However, this improvement is insufficient to obtain results comparable to those of the memory four codes of Fig. 6.

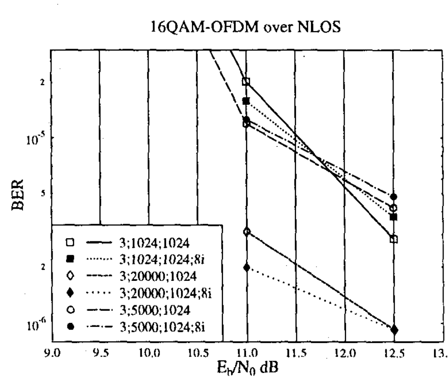

Fig. 7. Effect of the number of iterations and of the interleaver depth on the various 16QAM TCM and TTCM schemes over the NLOS channel of Table II. For legends refer to Figure 3.

Finally, in Fig. 8 we studied the effects of the channel interleaver. Comparing the performance of the system with and without channel interleaver - where the curves without interleaver are denoted by a .noi suffix in the legend - it is clear that a channel interleaver is mandatory in both the TTCM and the TCM schemes, and that the internal interleaver of the TTCM scheme cannot render the channel interleaver redundant.

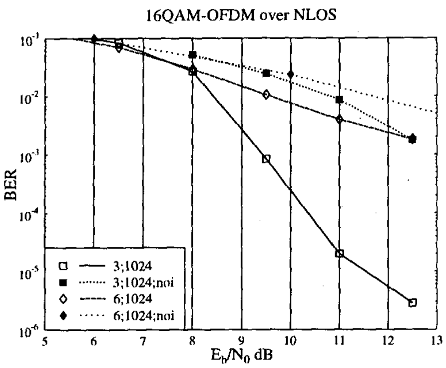

Fig. 8. Effect of the channel interleaver on 16QAM TCM and TTCM over the NLOS channel of Table II. For legends refer to Figure 3.

C. UMTS channel

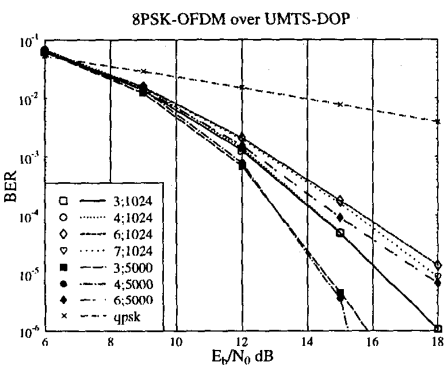

Fig. 9. Effect of the channel interleaver on 8PSK TCM and TTCM over the UMTS channel of Table II. For legends refer to Figure 3.

Fig. 9 reports our results obtained over the UMTS channel for 8PSK. In this hostile environment the gain of the TTCM scheme over TCM is less pronounced. Nevertheless, an E_b/N_0 gain in excess of three dB can be attained at a BER of 10^{-5}. An important conclusion is that over the UMTS channel the block dimension is more important, while the code memory has only a minor impact on the BER. This is due to the fact that in conjunction with longer block dimensions it is less likely that the entire block coincides with a hostile channel segment. In this case some of the symbols will be received correctly and the decoder becomes more effective in recovering the symbols transmitted on the poor-quality subcarriers. The same conclusions are valid, when considering 16QAM, as seen in Fig. 10. In addition, the gain of TTCM over TCM is higher, than in the context of 8PSK.

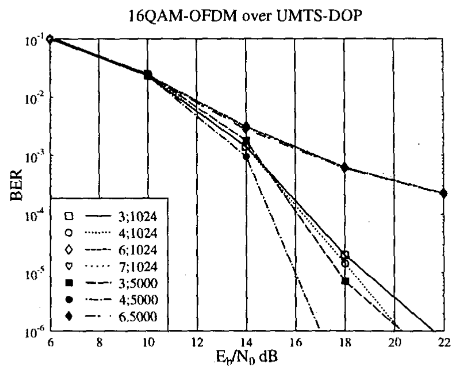

Fig. 10. Effect of the channel interleaver on 16QAM TCM and TTCM over the UMTS channel of Table II. For legends refer to Figure 3.

V. Conclusions

In conclusion, the TTCM-OFDM scheme constitutes a more attractive solution, than the TCM-OFDM scheme, however its attainable gain varies, depending on the channel. The memory length of the codes was important over the AWGN and the NLOS channel, and increasing it effectively reduces the error floor exhibited by the turbo coded systems. The block length had only a minor impact on the performance over the NLOS channel. By contrast, over the fading UMTS channel the block dimension was a key parameter in determining the performance, while the code memory had almost no effect. This was partly due to the higher grade of diversity that was achieved by using a longer channel interleaver and partly a consequence of the better performance of turbo-coded systems in conjunction with longer block dimensions.

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