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UTTCM-based optimization of coded communication system

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Abstract
In this paper, the parameters of two blocks of a coded transmission system are optimized. These blocks are the channel encoding block named “Unpunctured Turbo Trellis-Coded Modulation” (UTTCM), and “Zero-Forcing” (ZF) and “Minimum Mean Square Error” (MMSE) channel equalization block. The optimization of the parameters of equalization and encoding blocks is based on simulations over Proakis “B” selective frequency channel.

1. Introduction

In digital communication system, given in Fig. 1 [1], every element is optimized to one purpose: having the best performance according to a chosen transmission channel. Considering a selective frequency channel, a block named “Equalizer” is added; its role is to minimize the effect of “Inter-Symbol Interferences” (ISI) [1].

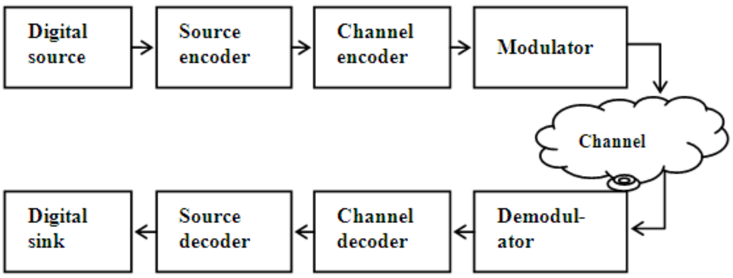

Figure 1. *Digital communication system.*

In this paper, two elements of the transmission chain are studied: 1) channel encoder represented by a TCM-based turbo encoder called “Unpunctured Turbo Trellis-Coded Modulation” (UTTCM) [2], and 2) linear equalizer represented by a digital filter obtained by two methods: “Zero-Forcing” (ZF) equalizer and “Minimum Mean Square Error” (MMSE) Equalizer [1].

The necessity to introduce the equalization into the reception part of the transmission chain was largely exposed in the literature. As practical utilization, we find the MMSE-Time-domain Equalizer (MMSE-TEQ) which is used in Asymmetric Digital Subscriber Line ADSL [3] to inverse the effect of transmission channel; and Minimum Likelihood Sequence Equalization (MLSE) which is used in Global System for Mobile communication (GSM) channel [4].

UTTCM encoder was proposed in 2007, and its design was improved in 2013 [2].

Over AWGN channel, this encoder permits to approach Shannon limit by approximately 1 dB for throughputs of 2, 3, 4, 5 and 6 bits per symbol (bps) and outperforms both Parallel Concatenated Trellis-Coded Modulation (PCTCM [5]) and Turbo Trellis-Coded Modulation (TTCM [6]).

In order to investigate the performance of UTTCM encoder over frequency selective channel, theoretical Proakis B channel is considered. This channel is shown as a good example for its short impulse response (three coefficients) and its hard selectivity.

2. Setting of UTTCM Codec Parameters

The UTTCM turbo encoder, as presented in [2] and shown in Fig. 2, is a parallel concatenation of two 2^{ν}-state rate $m / m+1$ convolutional encoders [7] separated by a random interleaver (ν denotes the memory order of the convolutional encoders). At the mapper input, the mapped bits are: 1) the m deinterleaved input bits, 2) the parity bit obtained from the convolutional encoder C_1, and 3) the parity bit obtained from the convolutional encoder C_2 after interleaving the m input bits.

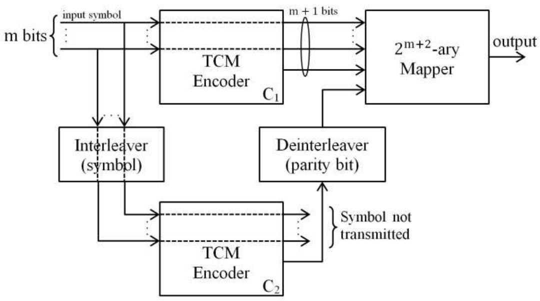

Figure 2. *Turbo encoding scheme of UTTCM.*

In order to achieve best performances of the encoding scheme, two mapping techniques were proposed (examples of 16-QAM mapper are shown in Fig. 3). When the first mapping technique adopts Gray mapping, the second combines both naturel mapping and Gray mapping and called Ungerboeck-Gray mapping [8]. For a chosen mapping technique, an exhaustive search in the trellis of the convolutional encoders permits to obtain the best encoders' generator polynomials ($h_0, h_1, \dots, h_m$) that achieve the highest square free Euclidean distance (d_f^2) [7].

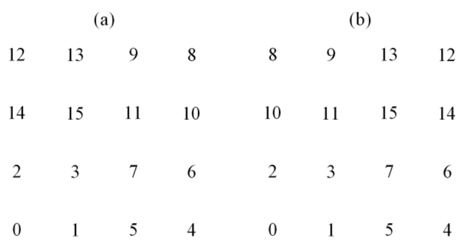

Figure 3. *Labeling for 16-QAM constellation. (a) Ungerboeck-Gray mapping, (b) Gray mapping.*

In table 1, the best 8-state rate $m / m+1$ constituent encoders' generator polynomials are given for a throughput of $m = 2$, 3 and 4 bps, and Gray mapping [2].

Table 1. *Best 8-state rate $m / m+1$ constituent encoders' generator polynomials*

m	Generator polynomials					Mapping	d_f^2
	h_0	h_1	h_2	h_3	h_4		
2	13	11	05	-	-	16-QAM	3.60
3	13	11	05	13	-	32-QAM	0.40
4	13	11	05	03	16	64-QAM	0.86

It can be observed from table 1 that the polynomials h_0, h_1 and h_2 are the same for all considered throughputs; which means that starting from generator polynomials of throughput 2 bps, we simplify the search time for throughputs 3 and 4 bps by choosing the first polynomials equal to those of throughput 2 bps.

Because of its reduced complexity and highest free distance, the considered throughput for simulation is 2 bps.

The decoder of UTTCM, depicted in Fig. 4, is a serial concatenation of two constituent symbol-by-symbol Maximum A Posteriori (MAP) decoders. The iterative decoding process is based, as explained for TTCM in [6], on transferring the (extrinsic & systematic) information between both constituent decoders.

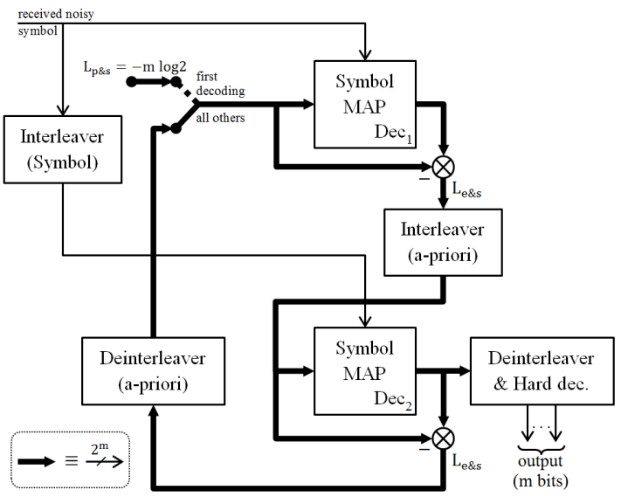

Figure 4. *Iterative decoding scheme of UTTCM.*

Considering the total received sequence of length $\underline{y} = \{y_1, \dots, y_N\}$, each constituent decoder has to compute, at each step k, the probability $\Pr\left\{d_k = i \middle| \underline{y}\right\}$ ($i \in \{0, \dots, 2^m - 1\}$) given by [6]

$$\Pr\left\{d_k = i \middle| \underline{y}\right\} = \text{const} \sum_{M} \sum_{M'} \gamma_i(y_k, M', M) \cdot \alpha_{k-1}(M') \cdot \beta_k(M)$$

where, d_k is a group of m information bits at step k, $\alpha_{k-1}(M')$ is the forward variable, $\beta_k(M)$ is the backward information and $\gamma_i(y_k, M', M)$ is the branch transition probability of the constituent encoder trellis given by

$$\gamma_i(y_k, M', M) = p(y_k|d_k = i, S_k = M, S_{k-1} = M')$$
$$\cdot q(d_k = i|S_k = M, S_{k-1} = M')$$
$$\cdot \Pr\{S_k = M|S_{k-1} = M'\}$$

S_k is the state, at step k, of constituent encoder trellis and the constant (const) can be eliminated by normalizing the sum over all i to unity.

According to the decoding process given in Fig. 4, the probability can be represented, in logarithm domain, by the sum of two terms: the a priori component $L_a(d_k = i)$, and the (extrinsic & systematic) component $L_{e\&s}(d_k = i)$ given by

$$L_a(d_k = i) = \log \Pr\{d_k = i\}$$

$$L_{e\&s}(d_k = i) = \log \Pr\left\{d_k = i \middle| \underline{y}\right\} - L_a(d_k = i)$$

In UTTCM decoder, the iterative decoding process is as follow: the (extrinsic & systematic) term ($L_{e\&s}$) generated at the output of the constituent decoder DEC_1 (respectively DEC_2) will be considered as a priori term (L_a) of the constituent decoder DEC_2 (respectively DEC_1), except for the very first decoding stage, where the constituent decoder DEC_1 sees at his input the (parity & systematic) term ($L_{p\&s}$); thus, at this stage, the a priori information is set to

$$\Pr\{d_k = i\} = \left(\frac{1}{2}\right)^m$$

i.e., the 2^m combinations of the symbol d_k are equally likely. All thin signal paths, in Fig. 4, are channel outputs; thick paths represent a group of values of 2^m logarithms of probabilities.

Each constituent decoder receives, at step k, a channel symbol y_k depending on m systematic bits, a parity bit produced by the relative encoder and an unknown parity bit produced by the other encoder. By denoting $b_k \in \{0,1\}$ the unknown parity bit at step k, the probability $p(y_k|d_k = i, S_k = M, S_{k-1} = M')$, part of the branch transition probability given in (2), is set to

$$p(y_k|d_k = i, S_k = M, S_{k-1} = M')$$
$$= \sum_{j\in\{0,1\}} p(y_k, b_k = j|d_k = i, S_k = M, S_{k-1} = M')$$
$$= \frac{1}{2}\sum_{j\in\{0,1\}} p(y_k|d_k = i, S_k = M, S_{k-1} = M', b_k = j)$$

where it is assumed that:

$$\Pr\{b_k = j|d_k = i, S_k = M, S_{k-1} = M'\} = \Pr\{b_k = j\} = \frac{1}{2}$$

i.e., the unknown parity bit in the symbol is statistically independent of d_k, S_k and S_{k-1}, and equally likely to be zero or one.

3. Setting of Equalizer Parameters

In digital communications, the purpose of introducing an equalizer (Fig. 5) in the transmission chain is to reduce inter-symbol interference to allow recovery of the transmit symbols. It may be a simple linear filter (FIR filter as in this study) or a complex algorithm. The following equalizers are adopted in this paper:

Minimum Mean Square Error (MMSE) equalizer: designs the filter to minimize $E[|e|^2]$, where e is the error signal, which is the filter output minus the transmitted signal [1].

Zero Forcing (ZF) equalizer: approximates the inverse of the channel with a linear filter [1].

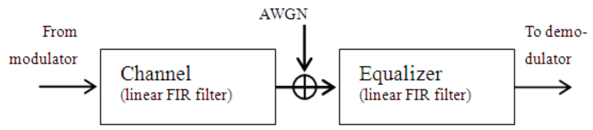

Figure 5. *Channel and equalizer scheme.*

As mentioned above, the adopted channel is a Proakis B selective Frequency channel [1]. Its impulse response is represented by the following coefficients:

B channel: 0.407 0.815 0.407,

and, the frequency response in Fig. 6. In order to show the hard selectivity of Proakis B channel, it is also plotted in Fig. 6 the frequency response corresponding to Proakis A channel.

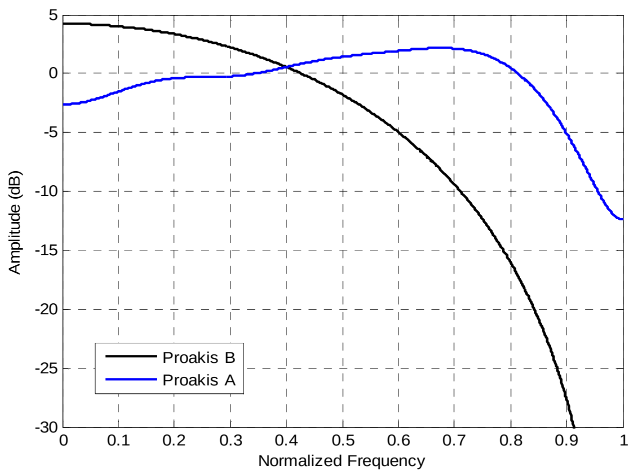

Figure 6. *Frequency response of Proakis A and B channels.*

4. Simulations and Discussions

In this section, the simulation results of the transmission chain employing UTTCM and ZF or MMSE equalizer are given and discussed in sense of Bit Error Rate (BER).

The parameters to be set in the transmission chain are: 1) the length of equalizer impulse response for ZF and MMSE equalizers, 2) the length of learning sequence for MMSE equalizer, 3) the spreading value (S) of turbo encoder interleaver, and 4) the spreading values of channel interleavers (S-interleaver [9] and Matrix interleaver [10]).

4.1. Setting of Equalizer Impulse Response Length

Fig. 7 illustrates the performance of UTTCM using MMSE equalizer with impulse response length $\mathrm{L_e}$ and learning sequence length ($\mathrm{L_l}$). Fig. 8 illustrates the performance of UTTCM using ZF equalizer with impulse response length $\mathrm{L_e}$. For both figures, the simulations were done for $\mathrm{SNR} = 26$ dB and 4 decoding iterations.

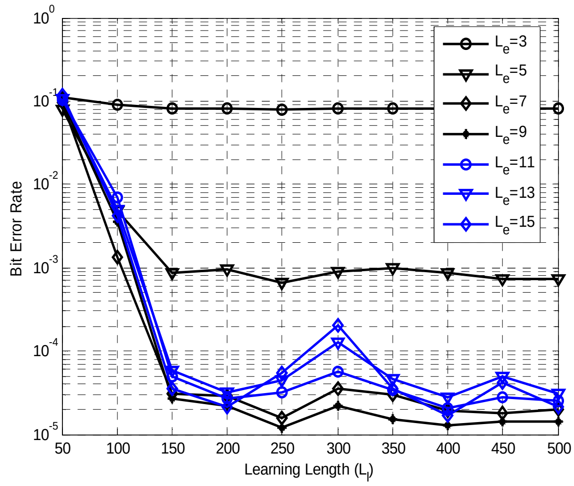

Figure 7. *Performance of UTTCM using MMSE equalizer according to the variation of Equalizer response length (L_e) and learning sequence length (L_l). Parameters of simulation: $SNR = 26$ dB and 4 decoding iterations.*

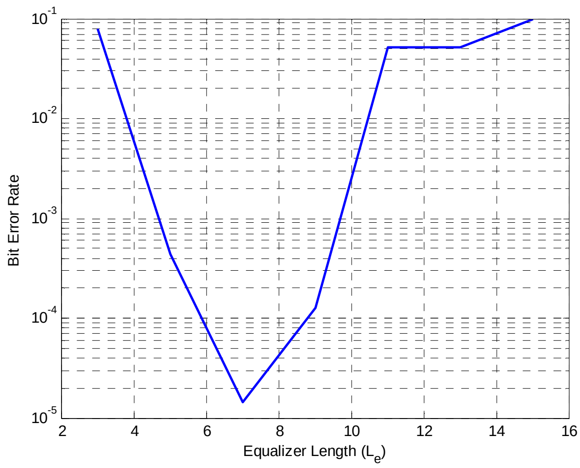

Figure 8. *Performance of UTTCM using ZF equalizer according to the variation of Equalizer response length (L_e). Parameters of simulation: $SNR = 26$ dB and 4 decoding iterations.*

It can be concluded from Fig. 7 and Fig. 8 that $\mathrm{L_e}$ equals 9 for MMSE equalizer and 7 for ZF equalizer, and $\mathrm{L_l}$ equals 250 symbols for MMSE equalizer.

4.2. Setting of Encoder Interleaver Spread Value

In Fig. 9, it is shown the performance of UTTCM using ZF or MMSE equalizer. In this case, the value of encoder interleaver spread is investigated. It can be observed that for both equalizers the value of S is the same and equals 23; this means that the choice of the encoder interleaver is independent of the considered transmission channel.

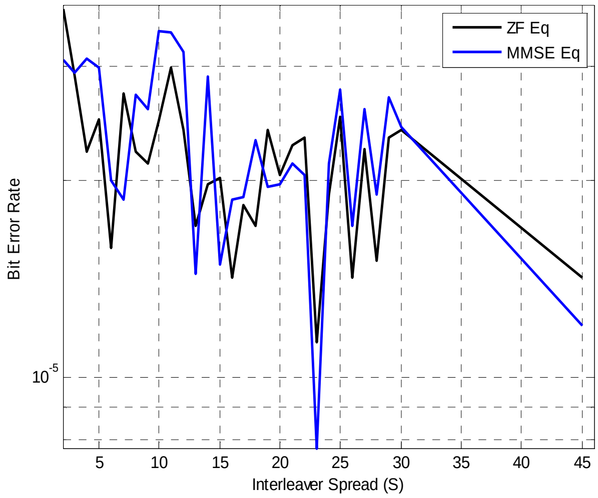

Figure 9. *Performance of UTTCM using ZF or MMSE equalizer according to the variation of encoder interleaver spread value (S). Parameters of simulation: $L_e(ZF) = 7$, $L_e(MMSE) = 9$, $L_l(MMSE) = 250$, $SNR = 26\ dB$ and 4 decoding iterations.*

4.3. Setting of Channel Interleaver Spread Value

In this section, two interleavers are used. The S-random interleaver (two adjacent symbols are interleaved into two positions separated by at least S symbols) [9], and Matrix interleaver (data is written into matrix lines and red into columns) [10].

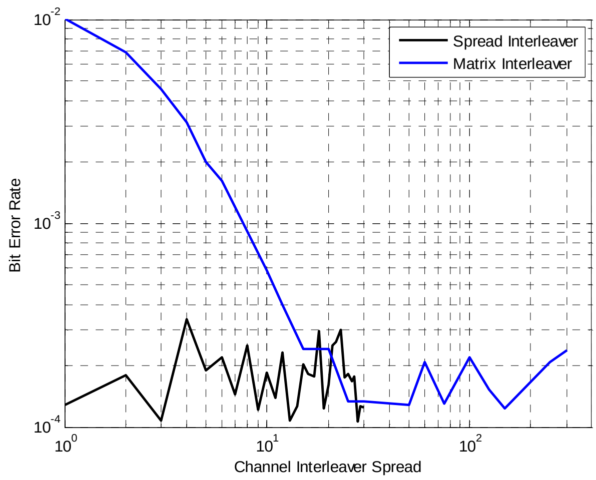

Figure 10. *Performance of UTTCM using ZF equalizer according to the variation of channel interleaver spread value (S). Parameters of simulation: $L_e = 7$, $SNR = 23$ dB and 4 decoding iterations.*

The simulation result of UTTCM using ZF equalizer is given in Fig. 10 for both spread and matrix interleavers. It can be shown that the efficiency of matrix interleaver is observed for a spread value up to 15 comparatively to spread interleaver. Another remark can be made concerning spread interleaver, where better error floors are achieved compared to matrix interleaver.

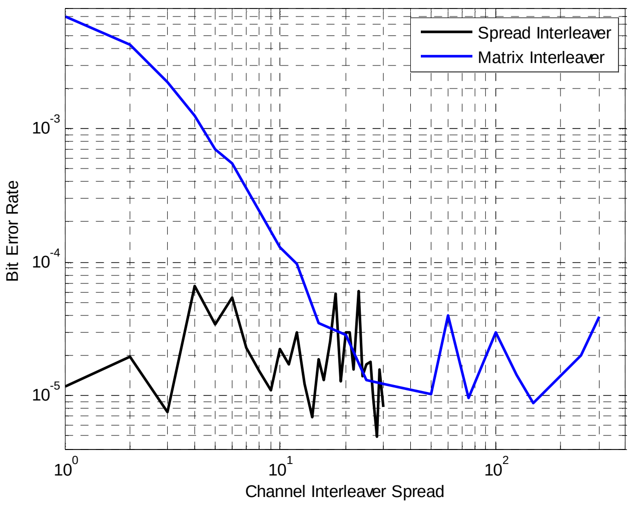

Figure 11. *Performance of UTTCM using MMSE equalizer according to the variation of channel interleaver spread value (S). Parameters of simulation:* $L_e = 9$, $L_l = 250$, $SNR = 23\ dB$ *and 4 decoding iterations.*

The simulation result of UTTCM using MMSE equalizer is given in Fig. 11 for both spread and matrix interleavers. It can be concluded that the same observations, as for ZF equalizer, can be made. According to the obtained results, the best value of the spread is 28 for spread interleaver and 150 for matrix interleaver regardless of selected channel.

4.4. Performance of UTTCM Using Optimized Transmission Chain Parameters

In Fig. 12 and Fig. 13, the performances of UTTCM are given for 4 and 6 decoding iterations. From Fig. 12, it is clear that the MMSE equalizer achieves better performances in sense of BER for 4 decoding iterations (an SNR gain of 0.5 dB is observed). From Fig. 13, obtained for 6 decoding iterations, we can remark the superiority of S-random interleaver; where at high SNRs, the performance curve obtained using S-random interleaver outperforms that obtained using matrix interleaver.

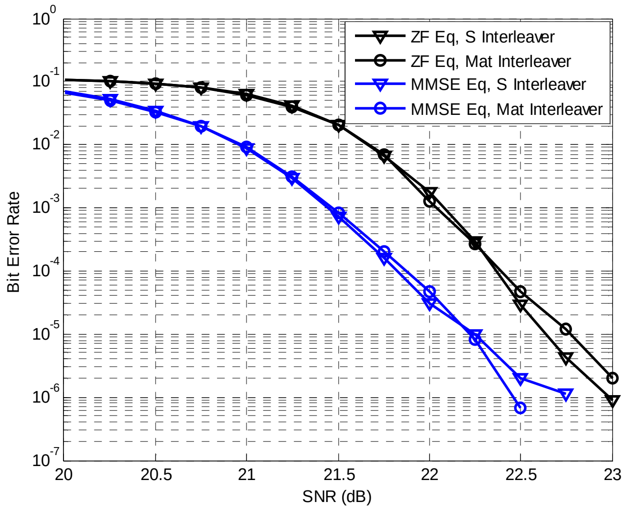

Figure 12. *BER Performance of UTTCM over Proakis B channel for 4 decoding iterations using the optimum simulation parameters.*

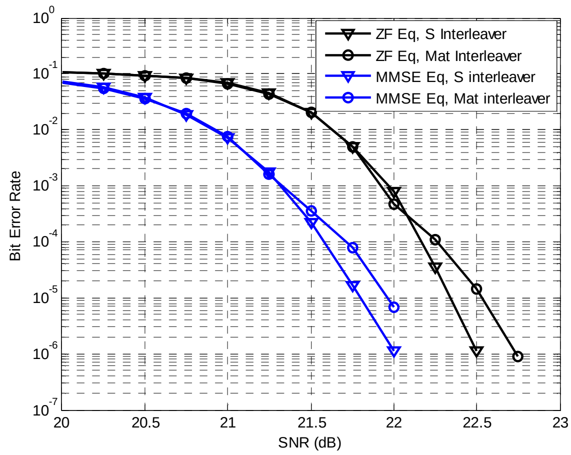

Figure 13. *BER Performance of UTTCM over Proakis B channel for 6 decoding iterations using the optimum simulation parameters.*

5. Conclusion

In this paper, the setting of UTTCM codec and equalizer is made over a Proakis B channel. ZF and MMSE equalizers are used. The considered parameters are: the equalizer response length, the learning sequence length for MMSE equalizer, the spread value of encoder and channel interleavers.

The simulations have shown that the use of MMSE equalizer and S-random interleaver, with the following parameters: equalizer response length $L_e = 9$, learning sequence length $L_l = 250$, encoder's interleaver spread value $S = 23$ and channel's interleaver spread value $S = 28$, allows to achieve an error floor of 10^{-6} considering 6 decoding iterations at $SNR = 22$ dB.

To improve the performance of the transmission chain using UTTCM, the number of decoding iterations is a good candidate.

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