BLOCK TURBO CODED BURST-BY-BURST ADAPTIVE MODEMS

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ABSTRACT

Wideband burst-by-burst adaptive modulation is applied in conjunction with a Decision Feedback Equalizer (DFE) in order to mitigate the effects of the slowly varying wideband multi-path Rayleigh fading channel in a noise-limited environment. Furthermore, turbo block coding is utilized in order to improve the Bit Error Rate (BER) and Bits Per Symbol (BPS) performance of the system. Two different turbo coded adaptive modulation systems employing different coding parameters are introduced and the merits of both systems are compared and contrasted.

1. INTRODUCTION

Burst-by-burst Adaptive Quadrature Amplitude Modulation (AQAM) employs a higher-order modulation scheme, when the channel is favourable, in order to increase the throughput and conversely, a more robust lower order modulation scheme is utilized to improve the mean Bit Error Rate (BER) performance, when the channel exhibits a deep fade. In a wideband channel, the Decision Feedback Equaliser (DFE) will eliminate most of the intersymbol interference (ISI). Consequently, the Signal-to-Noise Ratio (SNR) at the output of the equalizer, is calculated and used as a criterion to switch modulation modes. This ensures that the performance is optimised by employing equalization and AQAM techniques to combat signal power attenuation and ISI in a wideband channel. Recent developments in AQAM over a narrow-band channel include contributions by Webb and Steele [1] and Sampei *et al* [2]. This adaptive system can be conveniently implemented in a Time Division Duplex (TDD) environment, where the channel is slowly varying and reciprocal in nature.

The recently proposed turbo codes [3] are exploited to improve the BER and Bit Per Symbol (BPS) performance in a wideband AQAM system. In order to maximise the BPS throughput of the system, high code rates of above 2/3 are desirable. Consequently, block codes were chosen as the component codes in preference to Recursive Systematic Convolutional (RSC) codes, since turbo block coding has generally shown better results for coding rates above 2/3 [4]. Recent work on combining various conventional channel coding schemes with adaptive modulation has been reported by Matsuoka *et al* [5], Lau *et al* [6] and Goldsmith *et al* [7].

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2. SYSTEM OVERVIEW

At the receiver, the channel impulse response is estimated, which is then used to calculate the DFE coefficients [8]. In addition, both the channel estimate and the DFE coefficients are utilized to compute the pseudo-SNR at the output of the DFE. By assuming that the residual ISI is Gaussian distributed and that the probability of decision feedback errors is negligible, the pseudo-SNR at the output of the DFE, γ_{dfe} can be calculated as [9]:

$$\begin{aligned}\gamma_{dfe} &= \frac{\text{Wanted Signal Power}}{\text{Residual ISI Power} + \text{Effective Noise Power}} \\ &= \frac{E\left[|S_k \sum_{m=0}^{N_f} C_m h_m|^2\right]}{\sum_{q=-(N_f-1)}^{-1} E\left[|d_q S_{k-q}|^2\right] + N_o \sum_{m=0}^{N_f} |C_m|^2},\end{aligned} \tag{1}$$

where $d_q = \sum_{m=0}^{N_f-1} C_m h_{m+q}$, while C_m and h_m denote the DFE feed-forward coefficients and the channel impulse response, respectively. The transmitted signal and the noise spectral density are represented by S_k and N_o. Lastly, the number of DFE feed-forward coefficients is denoted by N_f. This calculated pseudo-SNR, γ_{dfe} is then compared against a set of modem mode switching threshold levels, f_n and subsequently the appropriate modulation scheme is selected for the next transmission burst.

BCH(n, k) codes are used as the component codes in the turbo encoder, where n and k denote the number of coded bits and the number of information bits, respectively. At the turbo decoder, the Log-MAP decoding algorithm [10] was utilized. The Log-MAP algorithm is merely a version of the MAP algorithm transformed into the log-domain, in order to reduce its complexity and the numerical stability problems associated with the MAP algorithm. A random turbo interleaver was utilized and the number of decoding iterations was set to six.

The multi-path channel model is characterized by its discretised symbol-spaced COST207 Typical Urban (TU) channel impulse response [12] as shown in Figure 2. Each path is faded independently according to a Rayleigh distribution and the corresponding normalised Doppler frequency is 3.27×10^{-5}. The DFE incorporated 35 forward taps and 7 feedback taps and the transmission burst structure used for our treatise is shown in Figure 1. In this contribution perfect channel estimation and perfect modulation mode selection was utilized.

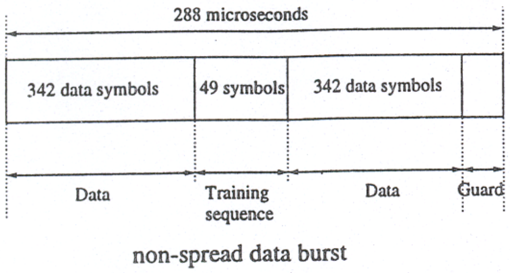


Figure 1: Transmission burst structure of the FMA1 non-spread data as specified in the FRAMES proposal [11].

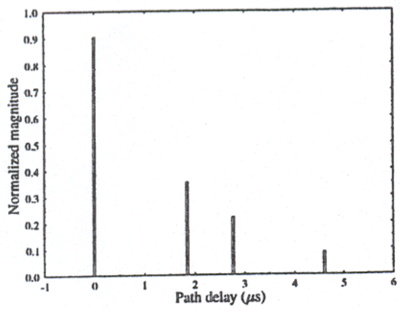


Figure 2: The impulse response of a COST 207 Typical Urban (TU) channel [12]

3. TURBO CODED ADAPTIVE MODULATION PERFORMANCE

In this section, we characterise the performance of two systems utilizing different turbo coding parameters. The generic switching mechanism is characterised by the modulation mode and its corresponding random turbo interleaver size and code rate as follows:

$$\text{Modulation Mode} = \begin{cases} NOTX & \text{if } \gamma_{DFE} < f_1 \\ BPSK, I_0, R_0 & \text{if } f_1 < \gamma_{DFE} < f_2 \\ 4QAM, I_1, R_1 & \text{if } f_2 < \gamma_{DFE} < f_3 \\ 16QAM, I_2, R_2 & \text{if } f_3 < \gamma_{DFE} < f_4 \\ 64QAM, I_3, R_3 & \text{if } \gamma_{DFE} > f_4 \end{cases}, \quad (2)$$

where $f_n, n = 1...4$ are the pseudo-SNR threshold levels, while I_n and R_n denote the random turbo interleaver size and the code rate for the corresponding modulation modes, respectively. In our first system, termed as System I, we will utilize a random turbo interleaver size of 9984 bits in conjunction with a fixed set of BCH(31,26) component codes for all modulation modes. In the second system, System II, the interleaver size and the component codes are varied according to the modulation mode selected, as shown in Table 1. The higher order modulation modes are assigned a higher code rate, in order to improve the data throughput at medium to high channel SNRs and conversely, the lower order modulation modes will be accompanied by lower code rates to ensure maximum error protection at low channel

Mod. Mode	BPSK	4QAM	16QAM	64QAM
BCH(n,k)	(31,26)	(31,26)	(63,57)	(127,120)
R_n	0.722	0.722	0.826	0.896
I_n	494	988	2223	3600

Table 1: The BCH component code with its corresponding code rate R_n and the interleaver size I_n for each modulation mode in System II, which was described by Equation 2.

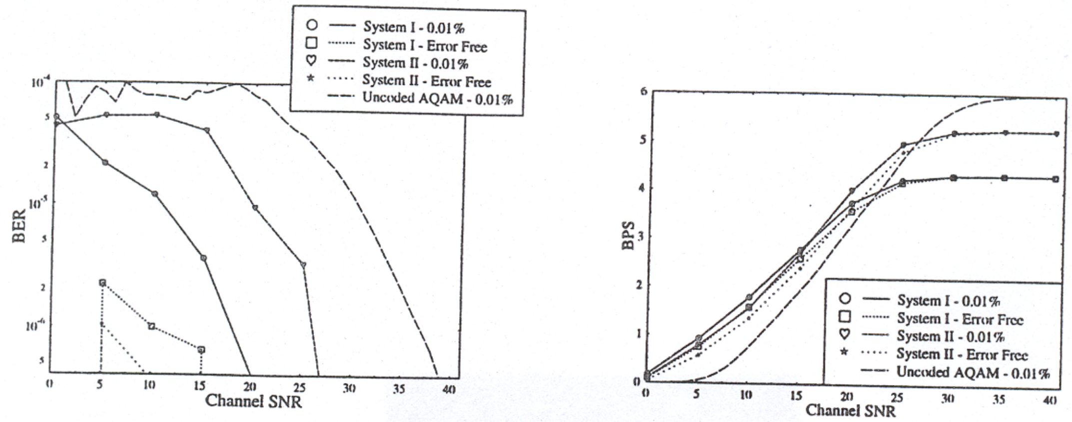
SNRs, where these modes will have a high selection probability. The turbo interleaver sizes were chosen to ensure burst-by-burst turbo decoding at the receiver. This will also ensure that the transmitted bits retain their original ordering, irrespective of the different component codes used. However, due to the longer codes used by the 16QAM and 64QAM modes, dummy bits are included, in order to ensure that the number of turbo encoded bits is equal to the transmission burst's capacity. These dummy bits can be used for conveying control or signalling information. Alternatively, these dummy bits can remain unused and we opted for this solution.

Target BER	Switching Thresholds			
	f_1	f_2	f_3	f_4
Uncoded $\leq 0.01\%$	8.30	10.45	16.88	23.05
System I				
Coded $\leq 0.01\%$	1.25	3.46	9.80	16.76
Error Free	2.25	4.46	10.80	17.76
System II				
Coded $\leq 0.01\%$	2.00	4.20	11.55	18.51
Error Free	3.25	5.46	12.80	19.76

Table 2: Turbo-coded AQAM switching thresholds, which were set to achieve a target BER of 0.01% or better, as well as for error-free transmission. The switching mechanism was characterized by Equation 2 and Table 1. The uncoded switching thresholds were optimised for maintaining a target BER of 0.01% according to [13].

The BER and BPS performances for both systems are shown in Figure 3, where the switching thresholds of the coded AQAM schemes were set according to Table 2. Due to the analytically intractable coded BER characteristics, the modem mode switching thresholds of the coded system were not optimised. Instead, these thresholds were set experimentally, in order to maintain a BER performance of below 0.01% or to achieve an error-free coded AQAM system performance.

In analysing the results, we will first compare the performance of System I and that of the individual fixed modulation schemes. In the individual fixed modulation modes the turbo component codes were two BCH(31,26) schemes and a random interleaver of size 9984 bits was chosen. The BER performance of each BCH(31,26)-coded modulation mode is shown in Figure 4. The corresponding BPS versus BER performance comparison is shown in Figure 5, where the BPS curve was plotted as a function of the required target BER. This Figure was generated by reading the required SNR for a given target BER from Figure 3(a) and finding the corresponding BPS value from Figure 3(b). As



(a) BER performance

(b) BPS performance

Figure 3: Turbo coded performance of **System I** and **System II**, where the generic system parameters were described in Section 3. The coded and uncoded AQAM switching thresholds were set according to Table 2 for maintaining a target BER of 0.01% and for an error-free system, respectively, using the switching regime of Equation 2

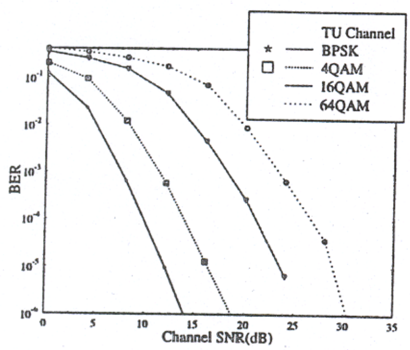


Figure 4: Turbo coded performance of the fixed modulation modes, where the random turbo interleaver size was set to 9984 bits and the BCH(31,26) component code was used

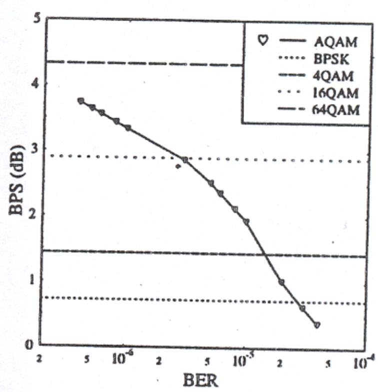


Figure 5: BPS versus BER performance of the individual fixed modulation modes and the AQAM **System I** using the switching regime of Equation 2. The corresponding switching threshold levels were listed in Table 2 for a target BER of below 0.01%.

seen in the Figure 3, the AQAM **System I** outperformed BPSK and QPSK in BPS terms for BERs lower than 10^{-5}. For the range of BERs below 2×10^{-6}, the BPS performance of **System I** was superior to that of 16QAM, while at lower BERs the BPS throughput converged to that of 64QAM.

Upon returning to Figure 3, the turbo coded AQAM performance is now compared to that of the uncoded AQAM system, where the uncoded switching thresholds were optimised using a similar method to that introduced by Torrance *et al* [13] in order to achieve a target BER of 0.01%, as shown in Table 2. According to Figure 3(a), **System I** provides a high SNR gain, but a limited maximum BPS of 4.3. The high SNR gain of approximately 20 dB observed across the BER range of about 5×10^{-7} 5×10^{-5} was achieved due to the large turbo interleaver size of 9984 bits and the relatively low coding rate of 0.722. However, the maximum BPS capacity was limited hence to 4.3. **System I** also exhibited a better BPS performance, than the uncoded AQAM for the channel SNR range of 0 to 22 dB.

System II provided an average SNR gain of approximately 10 dB across a wide range of BERs, when compared to the uncoded AQAM system. However, due to the utilization of higher coding rates for the higher order modulation modes and due to the reduced turbo interleaver size, the

BER performance was degraded, when compared to System I. However, at medium to high channel SNRs, the BPS performance improved to a maximum BPS capacity of 5.3, when compared to System I as a result of the higher coding rates employed in the $16QAM$ and $64QAM$ modes.

System I and System II were also optimised, in order to create a near-error-free communication system, as evidenced by Figure 3(a). The corresponding switching thresholds were chosen according to Table 2 and the BPS performance of System I and System II is displayed in Figure 3(b). At low to medium channel SNRs, the BPS performances of the near-error-free System I and System II degraded slightly, when compared to the System I and System II variants, which were targeted at a BER of below 0.01%.

4. CONCLUSION

We have demonstrated the application of turbo BCH coding in conjunction with AQAM in a wideband fading channel with fixed and variable coding rates, resulting in System I and a more complex System II, respectively. Both systems exhibited a better BPS performance from low to medium channel SNRs, when compared with the uncoded AQAM system. Furthermore, the BPS performance of System I was superior to the fixed modulation modes, as evidenced by Figure 5. In our current work, we are quantifying the effects of co-channel interference and channel quality estimation latency on the AQAM system.

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