ADAPTIVE OFDM TECHNIQUES FOR WIRELESS ATM AND UMTS SYSTEMS: BLIND MODEM MODE DETECTION AND TURBO CODING

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ABSTRACT

Sub-band adaptive OFDM modems are proposed and their performance is investigated using blind modem mode detection and turbo coding. Virtually error-free modem mode detection is achieved over Gaussian channels for Signal-to-Noise Ratios (SNR) in excess of about 10dB upon using one of four modem modes, namely 0, 1, 2 and 4 bits / symbol in each of the 16 subbands employed. The system can be configured for maintaining arbitrary target BERs, including virtually error-free communications, when adjusting the target number of bits / symbol transmitted.

1. ADAPTIVE OFDM MODEMS

Adaptive modulation was first suggested by Steele et al [1, 2] for exploiting the time-variant Shannonian channel capacity of fading narrowband channels. Further research was conducted on the topic for example at Osaka University and the Ministry of Post in Japan by Sampei et al [3], who invoked various channel coding and equalisation schemes, in order to optimise the system's performance. This work also led to the construction of a real-time test-bed. At CalTech in the USA Chua and Goldsmith [4] proposed the concomitant variation of both the modulation scheme and the transmitted power. A range of practical problems were solved by Torrance et al at Southampton University [5, 6], etc. Adaptive modulation was also incorporated in Orthogonal Frequency Division Multiplex (OFDM) modems, in order to adjust the number of modulation levels in accordance with the channel's frequency-domain transfer function, as it has been suggested by Czylwik et al [7], Chow et al [8], Rohling et al, Kammeyer et al and others [9].

The most straightforward framework for an adaptive OFDM scheme is a Time Division Duplex (TDD) system in a slowly varying reciprocal channel. Both the base and mobile stations transmit an OFDM symbol in turn, and at each station, the last received symbol is used for channel estimation in order to decide upon the modulation scheme to be adopted for the next transmitted OFDM symbol. The channel estimation can be performed for example by using the known pilots in Pilot Symbol Assisted Modulatio (PSAM). Here we initially assumed perfect knowledge o the channel transfer function during the received timeslot.

The modem mode of a given sub-band can be decide for example by comparing the average energy of the sub-bands to the fixed thresholds of Reference [10], which wer optimised for serial modems in order to maintain a give target Bit Error Rate (BER). Initially we employed thi regime, while deciding for the modem mode to be used o the basis of the lowest-quality subcarrier of a given sub-band. This resulted in a somewhat conservative estimation of the sub-band quality and modem mode, ultimatel yielding a lower BER than the original target value. Specifically, the Signal-to-Noise Ratio (SNR) thresholds for a give long-term target BER were determined by Powell's optimisation [10], assuming two uncoded target bit error rates: 1% for a high data rate "speech" system, and 10^{-4} for a highe intergrity, lower data rate "data" system. The resultin SNR thresholds $l_0 \ldots l_4$ for applying a given modulatio scheme M_n in a slowly Rayleigh fading channel for bot the above 'speech' and 'data' systems are given in Table 1 The modulation scheme M_n is selected, if the instantaneou channel SNR exceeds the switching level l_n.

	l_0	l_1	l_2	l_4
speech system	$-\infty$	3.31	6.48	11.61
data system	$-\infty$	7.98	10.42	16.76

Table 1: Optimised switching levels for adaptive modulation over Rayleigh fading channels for the "speech" an "data" system, shown in instantaneous channel SNR [dB (from [10]).

An alternative scheme taking into account the non-constant SNR values γ_n across the N_s subcarriers of a give sub-band can be devised by calculating the expected overal bit error probability for the given sub-band by averagin the individual carrier SNRs for all legitimate modulatio schemes M_n, yielding $\bar{p}_e(M_n) = 1/N_s \sum_j p_e(\gamma_j, M_n)$. Th scheme with the highest Bits per Symbol (BPS) throughput, whose estimated BER is lower than the required valu was then chosen. This algorithm allows the direct adjustment of the desired maximum BER, but the long-term bi

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OFDM FACHTAGUNG, BRAUNSCWEIG, GERMANY, 29-30 SEPT. 1998

error rate will be lower than the given threshold. The system performance for the sub-band BER estimator algorithm is portrayed along with our turbo channel coded results in Section 3.

However, the receiver requires the knowledge of the modem mode used in all frequency bands. The higher the number of frequency sub-bands, the more the system benefits from its adaptive nature, but a higher number of sub-band modem modes has to be signalled to the receiver. In case of a high number of sub-bands the number of modem mode signalling bits may in fact preclude the employment of such a regime, if explicit side-information is transmitted for sub-band modem mode signalling. Hence in Reference [9] we invoked a blind modem mode detection technique, which did not require explicit mode signalling and operated on the basis of estimating the SNR in all sub-bands.

By contrast, in this treatise we contribute in two areas, focusing our attention on an improved algorithm related to the blind detection of modem modes and on the effect of error correction coding on the adaptive OFDM modem performance.

The impulse response $h(\tau, t)$ for our experiments was generated on the basis of the symbol-spaced impulse response shown in Figure 1(a) by fading each of the impulses with a Rayleigh channel of a normalised maximal Doppler frequency of $f_d' = 1.235 \cdot 10^{-5}$, which corresponds to the channel experienced by a modem transmitting at a carrier frequency of 60 GHz with a sampling rate of 225 MHz and a vehicular velocity of 50 km/h. Explicitly, this channel was that of a 310 Mbit/s half-rate channel coded Wireless Asynchronous Transfer Mode (WATM) system. The frequency domain channel transfer function H_n corresponding to the unfaded impulse response is shown in Figure 1(b). Let us continue our discourse by considering our blind modem mode detection algorithms in the next Section.

2. BLIND DETECTION ALGORITHMS

Our blind detection algorithms aim to estimate the employed modulation scheme directly from the received data symbols, therefore avoiding the loss of data capacity due to signalling the modem modes. Two algorithms have been investigated, one based on geometrical SNR estimation, and another one incorporating convolutional error correction coding.

2.1. Blind detection by SNR estimation

According to this blind detection technique the receiver estimates the sub-band modem mode by quantising the de-faded received data symbols $R_n/\hat{H}_n$ in the block to the closest legitimate modulation symbol $\hat{R}_{n,m}$ for all possible modulation schemes M_m for each subcarrier index n in the current sub-band. The error energy e_m between the received symbol and the quantised symbol is evaluated for each legitimate modulation mode, as follows:

$$e_m = \sum_n \left(R_n/\hat{H}_n - \hat{R}_{n,m} \right)^2$$

and the modulation mode M_m, which minimises e_m is chosen for the demodulation of the block.

The modem mode detection error ratio (DER) of this blind detection scheme was evaluated for a 512 subcarrier OFDM modem in an AWGN channel, which is depicted in Figure 2. If the four modulation schemes M_0-M_3 are employed, then reliable detection of the modulation scheme is only guaranteed for SNR values in excess of 15–18 dB, depending on the number of sub-bands per OFDM symbol. If, however, only two modem modes, namely M_0 and M_1 are employed, then the DER is significantly improved. In this case, SNR values in excess of about 5–7 dB are sufficient to guarantee virtually errro-free detection. Let us now consider a higher-complexity, but more reliable blind-detection scheme.

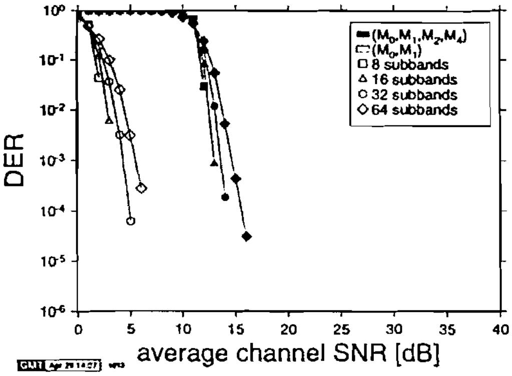


Figure 2: Probability of erroneous blind modulation scheme detection for systems employing (M_0, M_1) as well as for (M_0, M_1, M_2, M_4) for different block lengths in AWGN channel.

2.2. Blind detection by multi-level trellis decoder

If error correction coding is employed in the system, then the channel decoder can be invoked in order to estimate the most likely modulation scheme in each sub-band. As the number of bits per OFDM symbol is varying in this adaptive scheme, and the error correction encoder's block length therefore is not constant, for our proof of concept we have chosen a convolutional, rather than a block or turbo encoder at the transmitter. However, the same principle is applicable to the more complex and more powerful family of iterative turbo codecs. Once the modulation schemes to be employed in the various sub-bands are decided upon at the transmitter, the convolutional encoder is invoked, in order to generate a terminated convolutional code word of the length of the OFDM symbol's capacity expressed in terms of bits. This OFDM codeword is modulated on the OFDM subcarriers according to the different modulation schemes for the different sub-bands, and transmitted over the channel.

At the receiver, each received data subcarrier is demodulated by all possible demodulators belonging to M_0-M_3, and the resulting hard decision bits are fed into parallel trellises for Viterbi decoding. Figure 3 shows a schematic sketch of the resulting parallel trellis, if the following four modem modes, namely $M_1 \ldots M_4$ are employed for 16QAM (M_4), QPSK (M_2), BPSK (M_1), and "no transmission" (M_0) for a convolutional code having four states, for example. Each frequency-domain sub-band in the adaptive OFDM scheme corresponds to one of the four parallel trel-

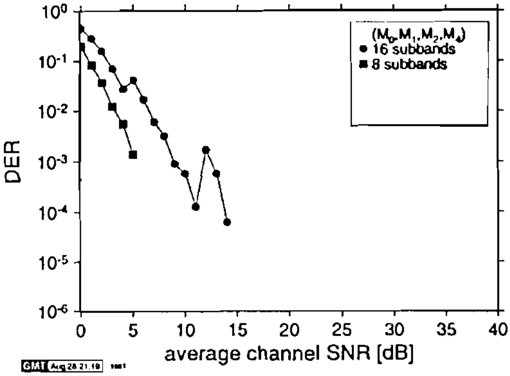


Figure 4: Probability of erroneous blind modulation scheme detection using the proposed parallel trellis algorithm with a $K = 7$ convolutional code over an AWGN channel.

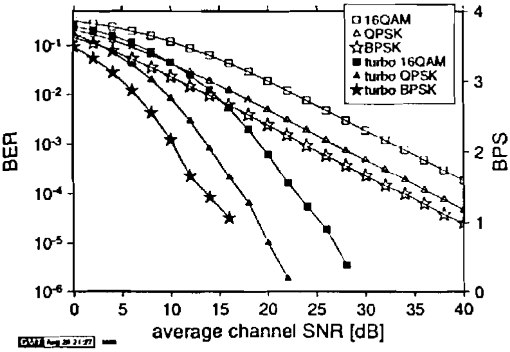


Figure 5: BER perfromance of OFDM modem in fading time–dispersive channel for both uncoded and turbo–coded transmission. 8–iteration turbo decoder, 1000 bit random interleaver, constraint length 3.

lises, whose inputs are generated independently by the four demodulators of the legitimate modulation schemes. The number of transitions in each of the trellises depends on the number of output bits from the different demodulators, and, as expected, the 16QAM (M_4) trellis contains four times as many transitions, as the BPSK and "no transmission" trellises. Since in case of "no transmission" no coded bits are transmitted, the state of the encoder does not change. Therefore the legitimate transitions for this case are only the horizontal ones.

At sub–band boundaries transitions are allowed between the same state of all the parallel trellises. This is not a transition due to a received bit, and therefore preserves the metric of the originating state. Note that in the Figure the possible allowed transitions are drawn only for the state 00; all other states generate the equivalent set of transitions. The initial state at the first block is 00 for all modulation schemes, and, as the code is terminated by 00, the last block's terminating states are also 00.

The receiver's decoder calculates the metrics for the transitions in the parallel trellises, and, once all data symbols have been processed, it traces back through the parallel trellis along the surviving path. This back-tracing commences at the most likely 00 state at the end of the last sub–band. If no termination was used at the decoder, then the back-tracing would commence at the most likely one of all the final states of the last block.

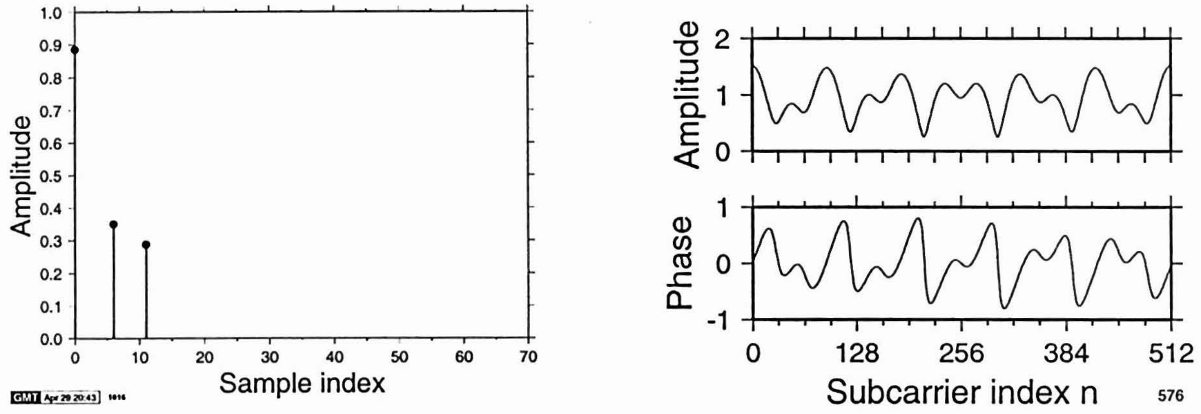
Figure 4 shows the probability of erroneous modulation mode estimation for the parallel trellis decoder in an AWGN channel for 16 and 8 sub–bands, if a convolutional code of constraint length 7 is used. Comparison with Figure 2 shows considerable improvements relative to the SNR-estimation based blind detection scheme of Reference [9], both for 16 as well as for 8 sub–bands. Higher sub–band widths improve the estimation accuracy by a greater degree, than it has been observed for the SNR-estimation based blind detection algorithm of Reference [9]. A modem mode detection error probability of less than 10^{-5} is observed for an SNR value of 6 and 15dB, respectively. The use of stronger error correction codes could further improve the estimation accuracy, at the cost of higher complexity. Lastly, we note that the spikes in the Figure around 6 and 11dB are due to opting for a higher-order constellation upon increasing the channel SNR, which then results in a slight increase of the DER. Let us now consider the overall coded system performance in the next Section.

3. SUB–BAND ADAPTIVE OFDM AND TURBO CODING

The main advantage of the proposed coded OFDM scheme is that the modem BER can be 'fine-tuned' to a value, where the full power of the error correction codec is exploited, but not overloaded. Specifically, the employment of adaptive OFDM modulation can reduce the modem's BER to a level, where channel decoders can perform reliably, since they are not overloaded by the plethora of channel errors. Figure 5 shows both the uncoded and coded BER performance of a 512 subcarrier OFDM modem in the fading wideband channel of Figure 1, assuming perfect channel estimation. The channel coding employed in this set of experiments is a turbo coder [11] having an interleaved data block length of 1000 bits, employing a random interleaver and 8 decoder iterations. The constituent recursive systematic convolutional (RSC) encoders are of constraint length 3, with octal generator polynomials of (7, 5).

By contrast, Figure 6(b) depicts the BER and Bits per Symbol (BPS) throughput performance of this turbo decoder employed in conjunction with the adaptive modem for different adaptation algorithms. Figure 6(a) shows the performance for the "speech" system employing the switching levels listed in Table 1. It can be seen that the channel coding results in a halved throughput compared to the uncoded case, but achieves error free transmission over the channel for SNR values near 0dB.

Intuitive tuning of the adaptation parameteres can achieve a better average throughput, while retaining error free data transmission. Figure 6(b) shows the performance for the same turbo decoder, with the adaptation algorithm employing the BER prediction method having an upper BER bound of 1%, rather than using the fixed thresholds of Table 1. It can be seen that the higher allowed uncoded BER when compared to Figure 6(a) leads to a significantly higher throughput for low SNR values. The turbo decoder still copes well with input BER values of up to 8%, resulting in a coded data BER of less than 10^{-5} for SNR values of



(a) $h(n)$

(b) H_n

Figure 1: Wideband channel (a) – unfaded symbol spaced impulse response (b) – corresponding frequency domain channel transfer function

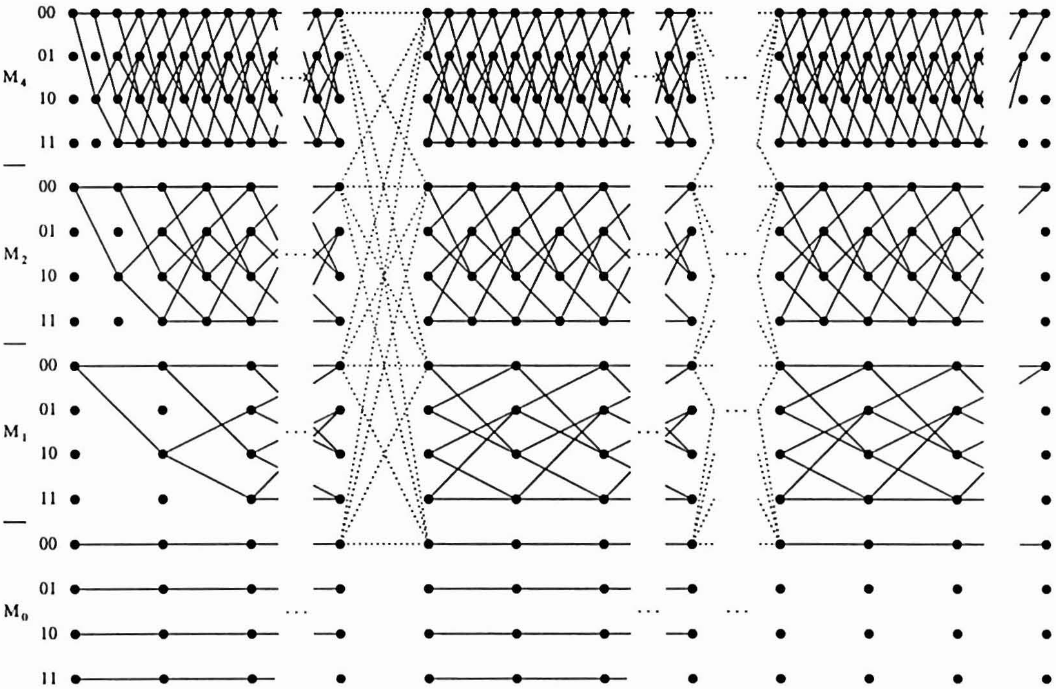
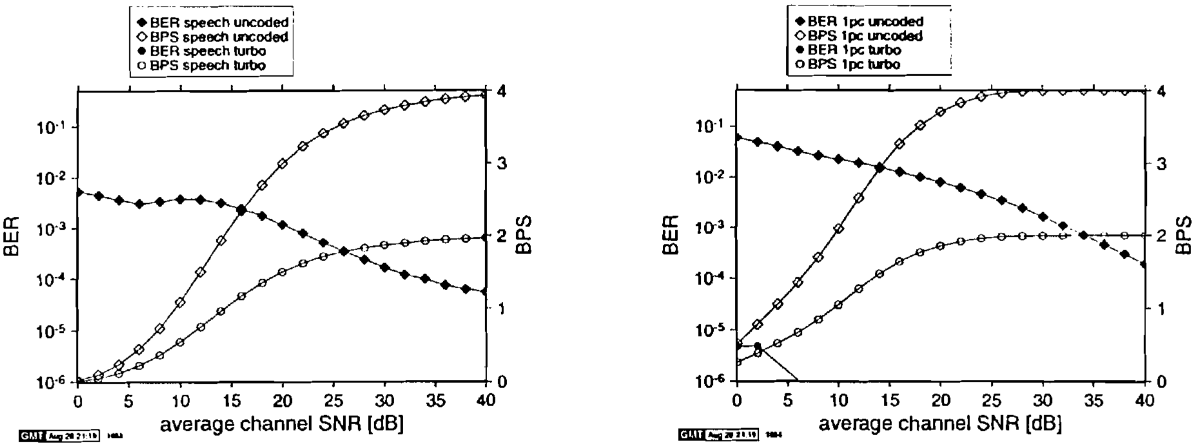


Figure 3: Schematic plot of the parallel trellis for blind modulation scheme detection. In this example, a four-state 00–terminated encoder was assumed. The dotted lines indicate the inter-block transitions for the 00 state, and are omitted for the other three states.



(a) speech system

(b) maximal BER 1%

Figure 6: BER and throughput of 16-subband adaptive turbo coded and uncoded OFDM modem employing (M_0, M_1, M_2, M_4) for (a) — speech type switching levels of Table 1 and (b) — a maximal estimated sub-band BER of 1%

under 3dB, and no recorded error events for SNR values above 6dB. In closing we note that the normalised Doppler frequency plays an important role in determining the performance of the adaptive OFDM modem, an issue, which was demonstrated in Reference [9].

4. CONCLUSIONS AND FURTHER WORK

An OFDM transmission scheme employing subband-adaptive modulation schemes for transmission over slowly fading time dispersive channels has been proposed. Two blind modulation scheme detection algorithms have been compared and the effect of turbo coding on the system's BER and BPS performance was quantified, confirming the advantages of the proposed adaptive schemes.

5. ACKNOWLEDGEMENT

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