BLIND-DETECTION ASSISTED SUB-BAND ADAPTIVE TURBO-CODED OFDM SCHEMES

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ABSTRACT

Burst-by-burst adaptive OFDM modems efficiently combat the effects of strong time-variant multipath interference. 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 sub-bands employed. The system can be configured for maintaining arbitrary target BERs, including virtually error-free communications, when adjusting the target number of bits per OFDM symbol transmitted.

1. ADAPTIVE OFDM MODEMS

Employing burst-by-burst adaptive modulation was proposed by Steele and Webb [1, 2] for transmissions over Rayleigh-fading narrow band channels, stimulating further work both in Japan by Sampei *et al* [3] and in the USA by Goldsmith *et al* [4]. 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* [5], Chow *et al* [6], Rohling *et al*, Kammeyer *et al* and others [7].

Burst-by-burst adaptive modulation exploits the time-varying nature of the wireless communications channel, invoking the the following modem functions:

- Channel quality estimation,
- Choice of the appropriate modulation scheme, and
- Either explicit signalling or inferring the modulation modes by invoking blind mode detection.

Since the modem parameter adaptation is tailored to the current channel conditions between the transmitter and the receiver, this technique is essentially limited to point-to-point duplex communications. The perceived channel quality estimate of the receiver, or the set of corresponding modulation parameters has to be communicated to the transmitter in order to invoke the appropriate modem mode for its transmission, which results in the required receiver performance. In a duplex traffic scenario over a reciprocal channel this can be performed using an open loop adaptation control, where the most recent received packet is employed by the receiver, in order to estimate the channel quality and to choose the appropriate modulation parameters for its next transmission. In a non-reciprocal propagation environment, on the other hand, the set of parameters to be used for the next transmission has to be signalled by the receiver to the transmitter by superimposing this side-information on the corresponding reverse-direction packets. This introduces more latency, rendering the channel quality estimates more obsolete, than in case of the open-loop scenario.

In this contribution we will concentrate on open-loop adaptive modulation relying on the assumption of a reciprocal propagation scenario. We will assume 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 quality estimation, in order to decide upon the modulation scheme to be adopted for the next transmitted OFDM symbol. The channel quality estimation can be performed for example by using the known pilots in Pilot Symbol Assisted Modulation (PSAM). Here we initially assumed perfect knowledge of the channel transfer function during the received time slot.

In order to successfully demodulate the received data symbols, the adaptive receiver has to be aware of the modem mode used by the transmitter. This information can either be explicitly conveyed by the transmitted OFDM symbol, or the receiver can attempt to perform blind parameter estimation on the basis of the received data symbols.

Our proposed scheme invoked three different modulation schemes, as well as "no transmission", on a subcarrier by subcarrier basis. The decision concerning the modulation scheme to be used was based on the estimated Signal-to-Noise Ratio (SNR) of a subcarrier, which can be determined on the basis of the channel transfer function estimate of the corresponding subcarriers at the time of transmission. Ideally, this modulation scheme adaptation is car-

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ried out for each of the subcarriers independently, but the signalling overhead of such a system would be prohibitive. Therefore, we have grouped adjacent subcarriers into "sub-bands", and assigned the same modulation scheme to all subcarriers in that group. Note that the frequency domain channel transfer function might not be constant across the subcarriers in a sub-band, hence a subband-based parameter adaptation is sub-optimal for some of the subcarriers. This sacrifice in adaptation flexibility assists however in reducing the signalling overhead, or enables the employment of blind parameter detection techniques, as discussed below.

The channel model employed for the simulations consisted of a three-path impulse response, with a maximal delay of 11 samples, where each path was faded according to a Rayleigh distribution, using a normalised maximal Doppler frequency of $f'_d = 1.235 \cdot 10^{-5}$, which corresponds to the channel experienced by a Wireless Asynchronous Transfer Mode (WATM) modem transmitting at a carrier frequency of 60 GHz with a sampling rate of 225 MHz and a vehicular velocity of 50 km/h. The channel model used was discussed in [7].

1.1. Modulation Parameter Adaptation

The modulation mode for a given sub-band can be decided on the basis of a number of different algorithms, two of which are described below. Specifically, we used a *fixed switching level based as well as a target BER based approach.*

1.1.1. Fixed Switching Levels

Parameter adaptation based on comparing the sub-band channel SNR with a set of fixed switching thresholds, such as proposed by Torrance *et al* [8], can also be employed for adaptive OFDM modems. Torrance's thresholds were optimised for serial modems, in order to maintain a given target Bit Error Rate (BER) in slowly varying narrow-band Rayleigh fading channels. These Signal-to-Noise Ratio (SNR) thresholds were determined by Powell's optimisation for maintaining a given long-term target BER [8], namely assuming two uncoded target BERs: 1% for a more error-tolerant "speech" system, and 10^{-4} for a higher integrity and hence reduced-rate "data" system. The resulting SNR thresholds $l_0 \ldots l_4$ for applying a given modulation scheme M_n in a slowly Rayleigh fading channel for both the above 'speech' and 'data' systems are given in Table 1, where M_n indicates an n Bits-Per-Symbol (BPS) QAM scheme. As mentioned, "no transmission", BPSK, QPSK, and 16-QAM modes were used. The modulation scheme M_n is selected, if the instantaneous 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" and "data" system, shown in instantaneous channel SNR [dB] (from [8]).

Given the time- and frequency-variant channel quality within the sub-bands, we compare the lowest quality subcarrier in each sub-band with the thresholds of Table 1 for controlling the adaptation. This results in a conservative channel quality estimate, ultimately leading to a lower throughput and BER than the target values.

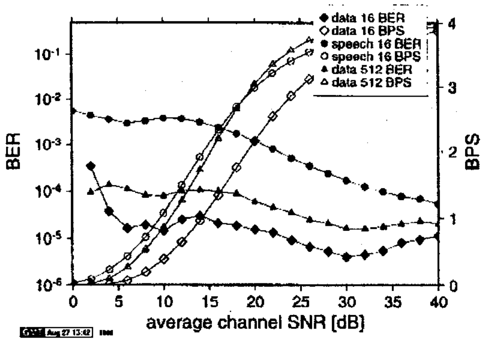

Figure 1: BER and throughput of 16 sub-band switching level adaptive OFDM modem employing BPSK, QPSK, 16-QAM and "no transmission" in Rayleigh fading time-dispersive channel.

Figure 1 characterises the performance of the adaptive modem under the channel conditions given above. The black markers in the figure indicate the long-term average BER, while the corresponding hollow markers denote the average throughput in terms of the number of Bits Per Symbol (BPS). It can be seen that arbitrary target BER levels can be met for all SNR values in a trade-off against the average throughput. The curves labeled "16" indicate the performance of the 16 sub-band adaptive modem, while the data labelled "512" corresponds to the subcarrier-by-subcarrier adaptive case for the "data"-.-type switching levels of Table 1. It can be seen that the subcarrier-by-subcarrier adaptive modem hits the target BER of 10^{-4} much more closely, than the sub-band adaptive scheme, and that its throughput is considerably higher, than that of the sub-band adaptive modem. The choice of the sub-band width in relation to the channel's coherence bandwidth allows a trade-off between the signalling overhead and the efficiency with which the modem exploits the available channel capacity.

1.1.2. Target BER Adaptation

An alternative scheme taking into account the non-constant SNR values γ_n across the N_s subcarriers of a given sub-band can be devised by calculating the expected overall bit error probability for the given sub-band by averaging the individual subcarrier BERs for all legitimate modulation schemes M_n, yielding $\bar{p}_e(M_n) = 1/N_s \sum_j p_e(\gamma_j, M_n)$. The scheme with the highest Bits per Symbol (BPS) throughput, whose estimated BER is lower than the required value was then chosen. This algorithm allows the direct adjustment of the desired maximum BER, but the long-term bit error rate will be lower than the given threshold. The system performance for the sub-band BER estimator algorithm is portrayed along with the turbo channel coded results at a later stage, in Section 3.

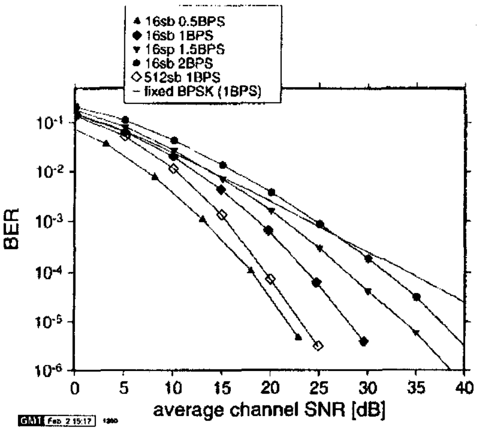

Figure 2: BER versus SNR for 512 subcarrier 16 sub-band constant throughput adaptive OFDM modem employing BPSK, QPSK, 16-QAM and "no transmission" in Rayleigh fading time dispersive channel for 0.5, 1, 1.5 and 2 Bits Per Symbol (BPS) target throughput.

1.1.3. Constant throughput adaptive OFDM

The time-varying data throughput of an adaptive OFDM modem operating with either of the two adaptation algorithms discussed above is problematic in a variety of applications. Fixed-rate real-time applications like speech or video transmission are very sensitive to the delays introduced by the necessary rate matching data buffering at the transmitter, and therefore different adaptation algorithms are needed for such applications.

The constant throughput AOFDM scheme proposed here exploits the frequency selectivity of the channel, while offering a constant bit rate. Again, sub-band adaptivity is assumed, in order to simplify signalling or blind detection of the modulation modes.

The modulation mode allocation of the sub-bands is performed on the basis of a cost function, based on the expected number of bit errors in each sub-band. The expected number of bit errors, $e_{n,s}$, for each sub-band n and each possible modulation mode s is calculated on the basis of the estimated channel transfer function $\hat{H}$, taking also into account the number of bits transmitted per sub-band and corresponding modulation mode $b_{n,s}$.

Each sub-band is assigned a state variable s_n holding the index of a modulation mode. Each state variable is initalised to the lowest order modulation mode, which in our case is 0 for "no transmission". A set of cost function values $c_{n,s}$ is calculated for each sub-band n and state s:

$$c_{n,s} = \frac{e_{n,s+1} - e_{n,s}}{b_{n,s+1} - b_{n,s}} \tag{1}$$

for all but the highest oder modulation mode s. This cost function value reflects the expected increase in the number of bit errors divided by the throughput increase achieved, if the next higher order modem mode is invoked instead of index s in sub-band n, quantifying the expected incremental BER of the state transition $s \rightarrow s+1$ in sub-band n.

The modulation mode adaptation is performed by repeatedly searching for the block n with the lowest value of c_{n,s_n}, and incrementing its state s_n. This is repeated, until the total number of bits in the OFDM symbol reaches the target number of bits. Due to the granularity in terms of the number of bits introduced by the sub-bands, the total number of bits may exceed the target. In this case, the data is padded with dummy bits for transmission.

Figure 2 gives an overview of the BER performance of the fixed throughput 512 subcarrier OFDM modem in our time dispersive channel for a range of target bit numbers. The graph without markers represents the performance of a fixed BPSK OFDM modem in the channel, which transmits 1 bit over each data subcarrier per OFDM symbol. The diamond-shaped markers give the performance of the equivalent-throughput adaptive scheme, both for the 16-subband scheme shown in black, as well as for the subcarrier-by-subcarrier adaptive scheme in white. It can be seen that the 16-subband adaptive scheme yields a significant improvement in BER for SNR values in excess of 10 dB. The SNR gain for a BER of 10^{-4} is 8 dB compared to the non-adaptive case. Subcarrier-by-subcarrier adaptivity increases this gain by a further 4 dB. The modem can easily be adapted to the system requirements by adjusting the target bit rate, as it is shown in Figure 2. Halving the throughput to 0.5 BPS, the BER performance improves by 6 dB for a BER of 10^{-4}, while increasing the throughput to 2 BPS deteriorates the noise resilience by 8 dB at the same BER.

1.2. Signalling and Blind Detection

The receiver requires the knowledge of the modulation modes used in the sub-bands, and this information has to be reliably signalled. Errors in the transmission of the signalling information not only lead to bit errors at the demodulation of the data symbols, but also result in possible loss of synchronisation in the data stream, as the number of bits in the sub-bands will be detected incorrectly. Signalling this information reliably requires a considerable amount of the system's capacity. Hence blind or implicit detection techniques assist in improving the system's data capacity.

2. BLIND DETECTION ALGORITHMS

Our blind detection algorithms aim to estimate the modulation mode employed directly from the received data symbols, therefore avoiding the throughput reduction due to explicitly signalling the modem modes. Two algorithms have been investigated, one based on geometrical SNR estimation, and another one incorporating convolutional error correction coding. As a benchmarker also a simple explicit signalling scheme is investigated.

2.1. Signalling

The simplest way of signalling the modulation mode employed in a sub-band is to replace one of the data symbols by an M-PSK symbol, where M is the number of possible modulation modes. In this case, reception of each of the legitimate constellation points directly signals the use of a particular modulation mode in the current sub-band. In our case, employing four modulation modes, and assuming perfect phase recovery, the probability of a signalling error, namely $p_s(\gamma)$, when employing a single signalling symbol is

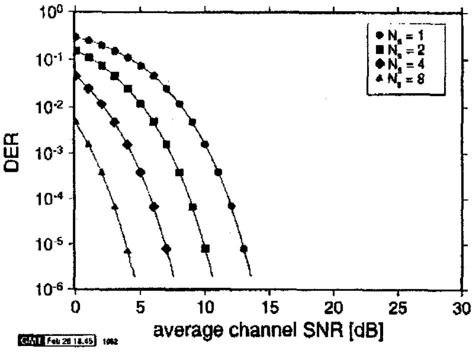

Figure 3: Probability of erroneous blind modulation scheme detection if signalling with maximum ratio combining is employed for QPSK symbols in an AWGN channel for 1, 2, 4, and 8 signalling symbols per sub-band.

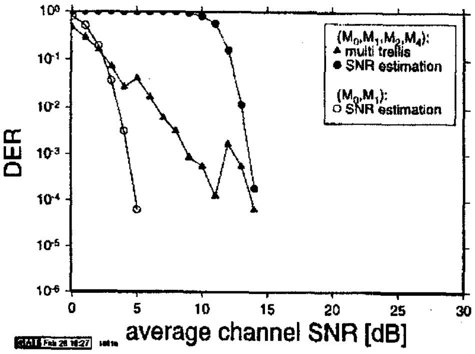

Figure 4: Probability of erroneous blind modulation scheme detection using the proposed parallel trellis algorithm with a $K = 7$ convolutional code and the SNR-estimation algorithm over an AWGN channel.

the symbol error probability of QPSK:

$$(1 - p_s(\gamma)) = (1 - p_{b,QPSK}(\gamma))^2,$$

where $p_{b,QPSK}$ is the bit error probability of QPSK:

$$p_{b,QPSK}(\gamma) = Q(\sqrt{\gamma}) = \frac{1}{2} \cdot \text{erfc}\left(\sqrt{\frac{\gamma}{2}}\right),$$

which leads to the following expression for the modulation mode signalling error probability:

$$p_s(\gamma) = 1 - \left(1 - \frac{1}{2} \cdot \text{erfc}\left(\sqrt{\frac{\gamma}{2}}\right)\right)^2.$$

The signalling error probability can be lowered by employing multiple signalling symbols and maximum ratio combining of the received signalling symbols $R_{s,n}$, yielding the decision variable R'_s prior to decision:

$$R'_s = \sum_{n=1}^{N_s} R_{s,n} \cdot \hat{H}^*_{s,n},$$

where N_s is the number of signalling symbols per sub-band, $R_{s,n}$ represents the received signalling symbols, and $\hat{H}_{s,n}$ denotes the estimated values of the frequency domain channel transfer function at the signalling subcarrier frequencies. Assuming perfect channel estimation and constant channel transfer function values across the group of signalling subcarriers, the signalling error probability for N_s signalling symbols can be expressed as:

$$p'_s(\gamma, N_s) = 1 - \left(1 - \frac{1}{2} \cdot \text{erfc}\left(\sqrt{\frac{N_s\gamma}{2}}\right)\right)^2$$

Figure 3 shows the signalling error rate in an AWGN channel for 1, 2, 4, and 8 signalling symbols per sub-band, respectively. As expected, doubling the number of signalling subcarriers improves the performance by 3dB. Detection error ratios (DER) below 10^{-5} can be achieved at 10dB SNR, if two signalling symbols are used. The signalling symbols for a given sub-band can be interleaved across the entire OFDM symbol bandwidth in order benefit from frequency diversity in fading wideband channels.

2.2. Blind detection by SNR estimation

According to this blind detection technique the receiver estimates the sub-band modulation mode by quantising the de-faded received data symbols $R_n/\hat{H}_n$ in the sub-band to the closest legitimate modulated symbols $\hat{R}_{n,m}$ for all possible modulation modes M_m and 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 modulation mode DER of this blind detection scheme was evaluated for a 512 subcarrier OFDM modem in an AWGN channel, which is depicted in Figure 4. If four modulation modes M_0-M_3 are employed, then reliable mode detection is only guaranteed for SNRs 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 error-free detection.

2.3. Blind detection by multi–level trellis decoder

If FEC coding is employed in the system, then the channel decoder can be invoked in order to estimate the most likely modulation mode in each sub-band. Since the number of bits per OFDM symbol is varying in this adaptive scheme, and the forward error correction (FEC) encoder's block length therefore is not constant, for the 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 coders. Once the modulation schemes to be employed in the sub-bands are decided upon at the transmitter, the convolutional encoder is invoked, in order to generate a terminated convolutional code word having a length corresponding to that of the OFDM symbol's capacity expressed in terms of bits. This codeword

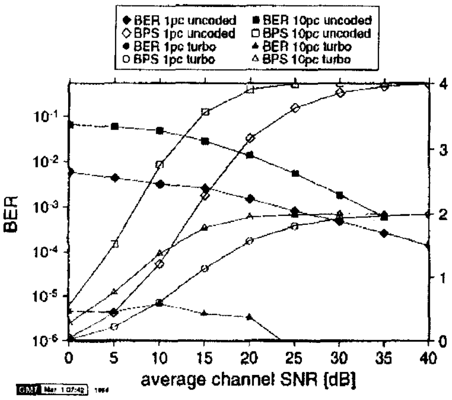

Figure 5: BER and throughput of 16-sub–band adaptive turbo coded and uncoded OFDM modem employing (M_0, M_1, M_2, M_4) for (a) — speech type switching levels of Table 1 and (b) — a maximal estimated sub–band BER of 1%

is then modulated onto the OFDM subcarriers according to the different modulation modes for the different sub–bands, and transmitted over the channel. At the receiver, the most likely sequence of modulation modes can be determined upon invoking the multiple trellis based technique of Reference [10]. The DER performance of this technique was plotted in Figure 4 for comparison with the SNR-based blind detection algorithm in an AWGN channel for 16 sub–bands, when a convolutional code of constraint length 7 was used. Comparison with the SNR-estimation based blind algorithm shows considerable improvements for the more complex multiple trellis based technique. A modulation mode detection error probability of less than 10^{-5} is observed for an SNR value of 15dB. The use of stronger error correction codes could further improve the DER, 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 decoder 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, without being overloaded by channel errors. The channel coding employed in this set of experiments was a turbo decoder [9] 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 $(7, 5)$.

Figure 5 depicts both the coded and uncoded BER and Bits per Symbol (BPS) throughput performance of this turbo decoder employed in conjunction with the adaptive modem. It can be seen that for a modem BER of 1% the turbo decoder ensures error free transmission, hence no marker can be seen in the figure. Furthermore, adjusting the algorithm's parameters can improve the throughput, while still guaranteeing a predefined BER. Forexample, adjusting the adaptation algorithm's target BER to 10%, the coded scheme reaches a significantly improved throughput while delivering an output BER of 10^{-4} and exhibiting a throughput of more than 0.5 data BPS at 2 dB SNR.

4. SUMMARY AND CONCLUSIONS

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

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