Adaptive Orthogonal Frequency Division Multiplexing Schemes

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Abstract

This paper investigates the upper–bound performance of subband-adaptive Orthogonal Frequency Division Multiplexing (OFDM) transmission in a time–dispersive channel and the feasibility of blind modulation scheme detection algorithms not requiring modulation scheme signalling information. Simulation results for a modem employing two and four modulation modes are presented using blind modulation mode detection.

1 Introduction and System Schematic

Steele and Webb [1] proposed adaptive modulation for exploiting the time-variant Shannonian channel capacity of fading channels, which stimulated further research at Osaka University by Sampei et al [2], at CalTech by Goldsmith et al [3] and at Southampton University [4, 5]. The associated principles can also be invoked in the context of parallel modems [6], [7], which is the topic of this contribution.

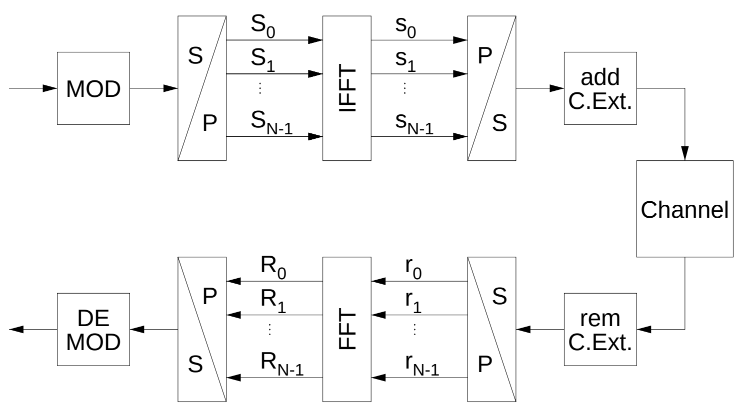
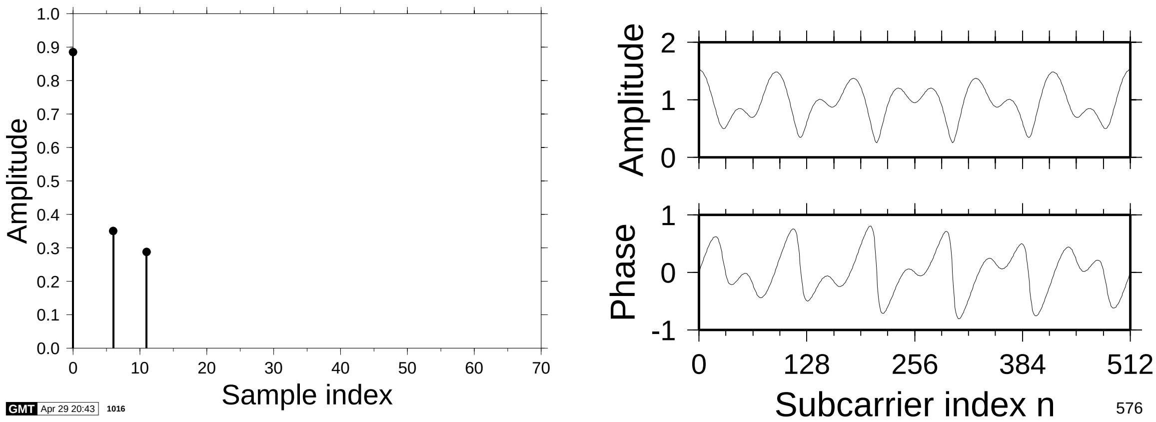


Figure 1: Schematic model of the OFDM system

The system model of the N–subcarrier Orthogonal Frequency Division Multiplexing (OFDM) modem is shown in Figure 1. At the transmitter, the modulator generates N data symbols S_n, $0 \leq n \leq N-1$, which are multiplexed to the N subcarriers. The time domain samples s_n transmitted during one OFDM symbol are generated by the Inverse Fast Fourier Transform (IFFT) and transmitted over the channel after the cyclic extension (C. Ext.) has been inserted. The channel is modelled by its time–variant impulse response $h(\tau, t)$ and addiitve white Gaussian noise (AWGN). At the receiver, the cyclic extension is removed from the received time–domain samples, and the data samples r_n are Fast Fourier Transformed to yield the received frequency–domain data symbols R_n.



(a) $h(n)$ (b) H_n

Figure 2: Wideband channel (a) – unfaded symbol spaced impulse response (b) – corresponding frequency domain channel transfer function

The channel's impulse response is assumed to be constant for the duration of one OFDM symbol, therefore it can be characterised for each OFDM symbol period by the N-point Fourier transform of the impulse response, which is referred to as the frequency domain channel transfer function H_n. The received data symbols R_n can be expressed as:

$$R_n = S_n \cdot H_n + n_n,$$

where n_n is an AWGN sample. Coherent detection is assumed for the system, therefore the received data symbols R_n need to be de–faded with an estimate of the channel transfer function H_n. This estimate $\hat{H}_n$ can be obtained by the use of pilot subcarriers in the OFDM symbol, or by the use of time–domain training sequences in the transmitted signal.

The impulse response $h(\tau, t)$ was generated on the basis of the symbol–spaced impulse response shown in Figure 2(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 sample rate of 225 MHz and a vehicular velocity of 50 km/h. The frequency domain channel transfer function H_n corresponding to the unfaded impulse response is shown in Figure 2(b). Here we refrain from further discussions concerning the components of OFDM modems, some of which were addressed for example in References [9]-[11] and focus our attention on adaptive OFDM in the next Section.

1.1 Adaptive modulation

The two communicating stations use the last received OFDM symbol to gain information concerning the frequency domain channel transfer function, and employ this information to determine the modulation parameters to be used for the next reverse link packet, therefore assuming reciprocity of the channel. The only variable parameter of our system was the choice of the modulation scheme out of a set of Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (16-QAM), as well as "No Transmission", for which no signal was transmitted. These modulation schemes are referred to as M_m, where $m \in (0, 1, 2, 4)$ is the number of data bits associated with one data symbol of each scheme.

In order to keep the system complexity low, the modulation scheme is not varied on a subcarrier–by–subcarrier basis, but instead the total OFDM bandwidth of 512 subcarriers is split into blocks of adjacent subcarriers, and the same modulation scheme is employed for all subcarriers of the same group. The choice of the modulation scheme for each group is determined by estimating the frequency domain channel transfer function $\hat{H}_n$ on the basis of the last received OFDM symbol and comparing the amplitude of the worst quality subcarrier with Signal–to–Noise (SNR) thresholds l_m for each of the modulation schemes

The receiver has no a–priory knowledge of the modulation scheme employed in a particular received block, and estimates this parameter by quantising the de–faded received data symbols $R_n/\hat{H}_n$ in the block to the closest symbol $\hat{R}_{n,m}$ for all possible modulation schemes M_m for each subcarrier index n in the current block. The decision–directed error energy e_m for each modulation scheme is calculated according to:

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

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

Clearly, the estimated frequency domain channel transfer function $\hat{H}_n$ is employed both for the selection of the modulation schemes at the transmitter, as well as for the modulation scheme detection and data demodulation at the receiver, and therefore its estimation accuracy has a great impact on the overall system performance. For the scope of this paper, perfect channel estimation is assumed.

2 Upper bound performance

The performance of the proposed, subband–adaptive, OFDM modem has been studied for a 512 subcarrier modem, similar to that of the ACTS Median system, employing 16 independent subbands over the symbol bandwidth. Initially, perfect channel estimation for both adaptive modulation scheme choice and demodulation as well as perfect signalling of modulation levels were assumed. Two different sets of switching levels l_m have been chosen, where each of the sets was optimised for different integroty requirements: one set, referred to as “speech”, is optimised to achieve bit error rates better than 1% at high throughputs, while the other set, optimised for “data” transmission, was optimised for a target bit error rate of 10^{-4} at the expense of a reduced throughput. These sets of switching levels have been proposed for adaptive serial modems in slowly varying narrowband channels by Torrance *et al.* [8]. Table 1 shows the respective switching levels in terms of channel SNR [dB] for both scenarios.

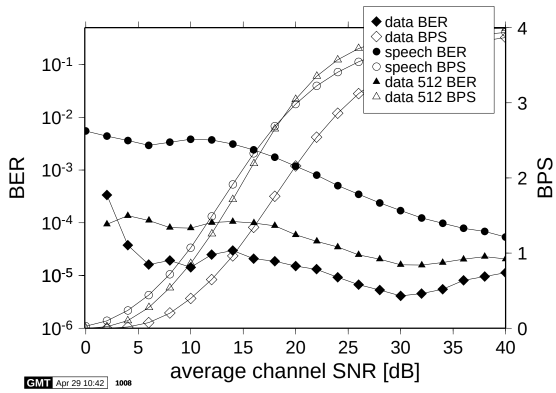
	l_0	l_1	l_2	l_4
speech system	$-\infty$	3.31	6.48	11.61
data system	$-\infty$	7.98	10.42	16.76

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]).

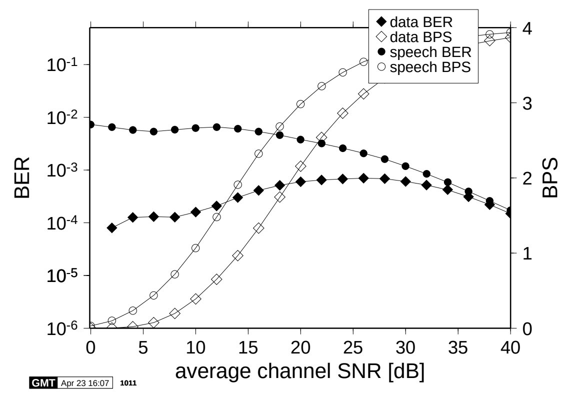
2.1 The effect of channel Doppler frequency

As the proposed adaptive OFDM modem employs the last received OFDM symbol to predict the frequency domain transfer function of the reverse channel for the next transmission, the quality of this perdiction suffers from changes of the channel transfer function between the uplink and downlink timeslots. We assume that the time delay between the up– and downlink slots is the same as the delay between the down– and uplink slots, and refer to this time as the frame duration T_f. We normalise the maximal Doppler frequency f_d of the channel to the frame duration T_f, and define the frame–normalised Doppler frequency F'_d as $F'_d = f_d \cdot T_f$. Figure 3 depicts the modem's BER and throughput performance in bits–per–symbol (BPS) for values of F'_d between $7.41 \cdot 10^{-3}$ and $2.3712 \cdot 10^{-1}$. These values stem from the studied system with a time slot duration of 2.67μs and up–/downlink delays of 1, 8, 16, and 32 timeslots at a channel Doppler frequency of 2.78 kHz.

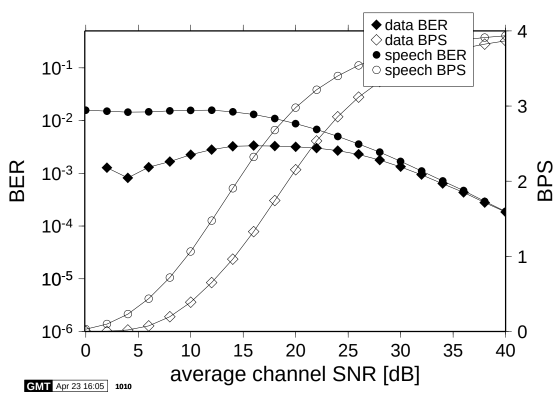
Figure 3(a) shows the BER and throughput of the studied modems in a framework with very low delay between up– and downlink timeslots. For $F'_d = 7.41 \cdot 10^{-3}$, the target bit error rates for the speech and data system are met for all SNR values above 4 dB, and the BER performance is generally better than the target error rates. This is explained by the conservative choice of modulation schemes based on the weakest subcarrier in each block. The comparison curves marked with triangles give the performance of a data modem with subcarrier–by–subcarrier modulation scheme adaptation. It can be observed that in this case the target error rates are met much more closely and that the throughput is considerably higher than that of the 16–subband system.



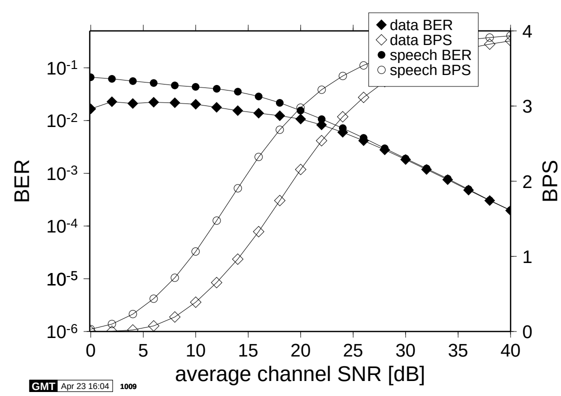
(a) $F'_d = 7.41 \cdot 10^{-3}$



(b) $F'_d = 5.928 \cdot 10^{-2}$



(c) $F'_d = 1.1856 \cdot 10^{-1}$



(d) $F'_d = 2.3712 \cdot 10^{-1}$

Figure 3: BER and throughput of 16-subband adaptive OFDM modem employing (M_0, M_1, M_2, M_4) for both data–type and speech–type switching levels and perfect modulation scheme detection and different frame normalised Doppler frequencies F'_d. The triangular markers in (a) show the performance of a subcarrier–by–subcarrier adaptive modem using the data–type switching levels for comparison.

It can be seen that the bit error rate performance for both the speech and the data system suffer from increasing decorrelation of the predicted and actual channel transfer function for increasing values of F'_d. The throughput is not affected by the variability of the channel.

3 Performance with blind detection of modulation scheme

The detection error probability of the blind modulation scheme detection algorithm described in Section 1.1 for a 512 subcarrier OFDM modem in an AWGN channel is depicted in Figure 4. If all four modulation schemes are employed, then reliable detection of the modulation scheme is only guaranteed for SNR values of more than 15–18 dB, depending on the number of blocks per OFDM symbol. If only M_0 and M_1 are employed, however, the estimation accuracy is much improved. In this case, SNR values above 5–7 dB are sufficient to guarantee reliable detection.

Figure 5 shows the BER perfromance of the data–type 16–subband adaptive system in the fading wideband channel for $F'_d = 7.51 \cdot 10^{-3}$ for both sets of modulation schemes, namely for (M_0, M_1) and (M_0, M_1, M_2, M_4) with blind modulation scheme detection. Erroneous decisions on the modulation scheme were assumed to yield a BER of 50% in the received block. This is optimistic, as in a real world scenario the receiver would have no knowledge of the number of bits actually transmitted, leading to loss

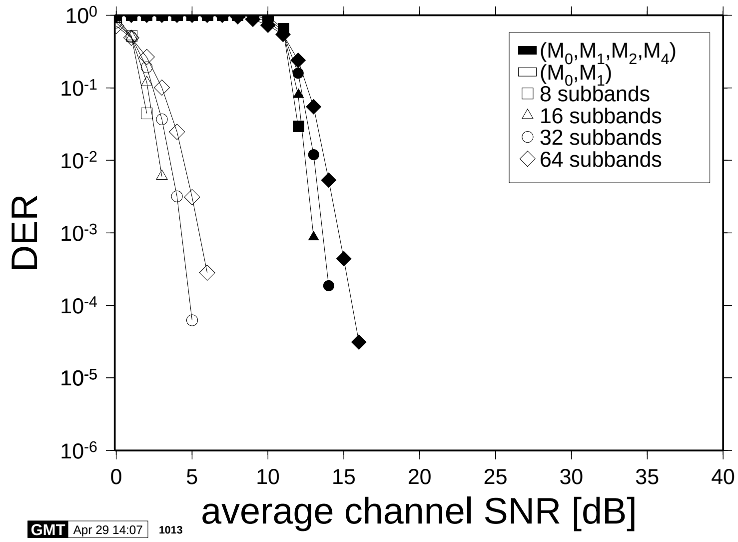


Figure 4: Probability of erroneous blind modulation scheme detection for systems employing (M_0, M_1) as well as for (M_0, M_1, M_2, M_4) for different block lengths in AWGN channel.

of synchronistion in the data stream. This problem is faced by all systems with variable throughput not employing an ideal reliable signalling channel, and must be mitigated by data synchronisation measures.

It can be seen from Figure 5 that while blind modulation scheme detection yields poor performance for the multi–level adaptive scheme, the two–level scheme exhibits very good BER results, consistently lower than 10^{-4}.

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. A simple blind modulation scheme detection algorithm has been examined, which allows signalling–free adaptation for a "No Transmission"/BPSK adaptive scheme.

It has been shown that the simple blind modulation scheme detection algorithm is vulnerable to channel impairments, if complex multi-level modem constellations, such as 16QAM or 64QAM have to be recognised. By contrast, if only two different modes, such as BPSK and No-Transmission have to be recognised, the blind detection scheme is extremely robust. Our current work is focused on integrating error correction coding in the blind modulation scheme detection algorithm, in order to improve its error resilience.

5 Acknowledgements

The financial support of Motorola ECID, Swindon, UK and that of the European Commission in the framework of the Median project is gratefully acknowledged. The authors are also indebted to the Median and First Consortium partners for fruitful discussions and for their friendship.

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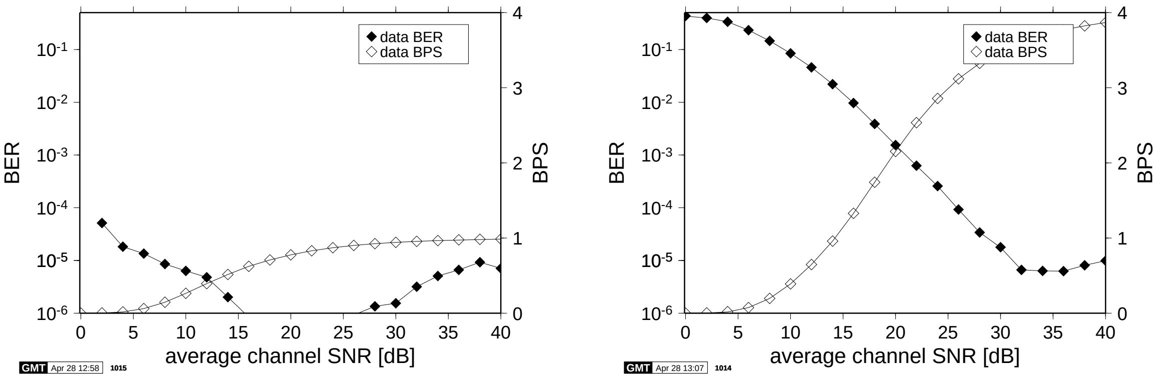

(a) (M_0, M_1)

(b) (M_0, M_1, M_2, M_4)

Figure 5: BER and throughput of 16-subband adaptive OFDM modem employing (a) — No Transmission (M_0) and BPSK (M_1) or (b) — (M_0, M_1, M_2, M_4), both for data–type switching levels and blind modulation scheme detection

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