CO-CHANNEL INTERFERENCE SUPPRESSION ASSISTED ADAPTIVE OFDM IN INTERFERENCE LIMITED ENVIRONMENTS

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ABSTRACT

This paper investigates the feasibility of Adaptive OFDM (AOFDM) transmissions in co-channel interference limited environments upon invoking the Sample Matrix Inversion (SMI) algorithm. The subcarrier based Signal-to-Noise Ratio (SNR), which can be derived from the SMI algorithm's weights is shown to be in most cases an effective measure for controlling the modulation mode adaptation. A simple pilot based scheme is introduced, which allows channel parameter estimation on an OFDM symbol-by-symbol basis. The system BER performance is shown to be improved by an order of a magnitude due to combining AOFDM with interference suppression.

1. INTRODUCTION

Signal fading as well as co-channel interference are known to have a severe impact on the system performance in multicellular mobile environments. *Adaptive modulation* as a method of matching the system to fading induced variations of the channel quality has originally been proposed for single carrier transmission, but its potential was also soon discovered in the context of multicarrier transmissions, with the aim of concentrating the throughput on subcarriers least affected by frequency selective fading [1]. On the other hand, adaptive antenna array techniques have been shown to be effective in reducing co-channel interference at the receiver side [2,3]. One of the most prominent schemes for performing the combining operation is the *Sample Matrix Inversion* (SMI) technique, which has recently drawn wide interest [4-6]. This treatise commences in the next section with a description of a system amalgamating adaptive modulation and co-channel interference suppression. Initial results will be presented in Section 3 assuming perfect knowledge of all channel parameters, whilst in Section 4 the problem of channel parameter estimation will be addressed by means of orthogonal pilot sequences, leading to our conclusions.

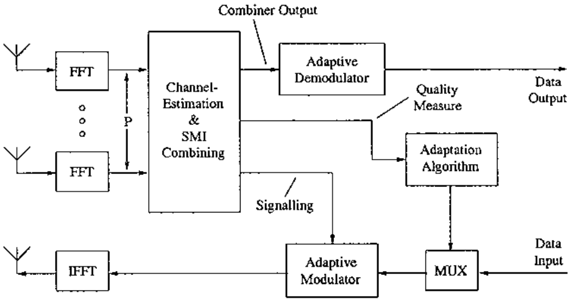

Figure 1: Schematic structure of the adaptive transceiver with interference suppression at the receiver

2. ADAPTIVE TRANSCEIVER ARCHITECTURE

An Overview - The transceiver schematic is shown in Figure 1, where the receiver employs a multiple-antenna assisted front end. The signal received by each individual antenna element is fed to an FFT block, and the resulting parallel received OFDM symbols are combined on a subcarrier-by-subcarrier basis. The combining is accomplished on the basis of the weight vector, which has been obtained by solving the Wiener equation, constituting the core of the sample matrix inversion algorithm [2,3]. After combining the signal is fed into the adaptive demodulator of Figure 1, which delivers the output bits in the form of soft-decision information to an optional channel decoder. The demodulator operates in one of a set of four modes, namely 'no transmission', BPSK, QPSK and 16-QAM. Since an interfered channel cannot be considered to constitute a reciprocal system, the modem mode adaptation operates in a closed-loop fashion, where each of the receivers instructs the remote transmitter as to the required set of modulation modes for the next AOFDM symbol, which is necessary for maintaining a given target Bits per Symbol (BPS) performance. On reception of a packet the adaptation algorithm

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computes the set of modulation modes to be employed by the remote transmitter for the next transmitted AOFDM symbol on the basis of a channel quality measure, namely the subcarrier SNR, which can be estimated by the interference suppression algorithm. The set of requested modulation modes is signalled to the remote receiver along with the next transmitted AOFDM symbol, which is then used by the remote transmitter in its next transmission.

The Signal Model - The $P \times 1$ vector of complex signals, $\mathbf{x}[n,k]$, received by the antenna array in the k-th subcarrier of the n-th OFDM symbol is constituted by a superposition of the independently faded signals associated with the *desired* user and the L *undesired* users plus the Gaussian noise at the array elements:

$$\begin{aligned}\mathbf{x}[n,k] &= \mathbf{d}[n,k]+\mathbf{u}[n,k]+\mathbf{n}[n,k], \quad \text{with} \qquad (1)\\ \mathbf{d}[n,k] &= \mathbf{H}^{(0)}[n,k]s_0[k]\\ \mathbf{u}[n,k] &= \sum_{l=1}^{L}\mathbf{H}^{(l)}[n,k]s_l[k],\end{aligned}$$

where $\mathbf{H}^{(l)}[n,k]$ for $l = 0,\ldots,L$ denotes the $P \times 1$ vector of complex channel coefficients between the l-th user and the P antenna array elements. We assume that the vector components $H_m^{(l)}[n,k]$ for different array elements m or users l are independent, stationary, complex Gaussian distributed processes with zero-mean and different variance σ_l^2, $l = 0,\ldots,L$. The variable $s_l[n,k]$ - which is assumed to have zero-mean and unit variance - represents the complex data of the l-th user and $\mathbf{n}[n,k]$ denotes the aforementioned $P \times 1$ vector of additive white Gaussian noise contributions with zero mean and variance σ^2 [6].

The SMI Algorithm - The idea behind minimum mean-square error (MMSE) beamforming [3] is to adjust the antenna weights, such that the power of the differential signal between the combiner output and a reference signal - which is characteristic of the desired user - is minimised. The solution to this problem is given by the well-known Wiener equation, which can be directly solved by means of the SMI algorithm in order to yield the optimum weight vector $\mathbf{w}[n,k]$ of dimension $P \times 1$. Once the instantaneous correlation between the received signals, which is represented by the $P \times P$ matrix $\mathbf{R}[n,k]$ - and the channel vector $\mathbf{H}^{(0)}[n,k]$ of the desired user become known, the weights are given by [3,4,6]:

$$\mathbf{w}[n,k] = (\mathbf{R}[n,k]+\gamma\mathbf{I})^{-1}\mathbf{H}^{(0)}[n,k], \qquad (2)$$

where γ represents the so-called diagonal augmentation factor [6]. Assuming knowledge of all channel parameters and the noise variance σ^2, the correlation matrix can be determined by:

$$\begin{aligned}\mathbf{R}[n,k] &\triangleq E_c\{\mathbf{x}[n,k]\mathbf{x}^H[n,k]\} \qquad (3)\\ &= \mathbf{R}_d[n,k]+\mathbf{R}_u[n,k]+\mathbf{R}_n[n,k], \quad \text{with}\\ \mathbf{R}_d[n,k] &= \mathbf{H}^{(0)}[n,k]\mathbf{H}^{(0)^H}[n,k]\\ \mathbf{R}_u[n,k] &= \sum_{l=1}^{L}\mathbf{H}^{(l)}[n,k]\mathbf{H}^{(l)^H}[n,k]\\ \mathbf{R}_n[n,k] &= \sigma^2\mathbf{I},\end{aligned}$$

which is a superposition of the correlation matrices $\mathbf{R}_d[n,k]$, $\mathbf{R}_u[n,k]$ and $\mathbf{R}_n[n,k]$ of the desired and undesired users as well as of the array element noise, respectively. The combiner output can now be inferred from the array output vector $\mathbf{x}[n,k]$ by means of:

$$y[n,k] = \mathbf{w}^H[n,k]\mathbf{x}[n,k]. \qquad (4)$$

The Signal-to-Noise Ratio (SNR) at the combiner output - which is of vital importance for the modulation mode adaptation - is given by [3]:

$$\begin{aligned}SNR &= \frac{E\{|\mathbf{w}^H[n,k]\mathbf{d}[n,k]|^2\}}{E\{|\mathbf{w}^H[n,k]\mathbf{n}[n,k]|^2\}} \qquad (5)\\ &= \frac{\mathbf{w}^H[n,k]\mathbf{R}_d[n,k]\mathbf{w}[n,k]}{\mathbf{w}^H[n,k]\mathbf{R}_n[n,k]\mathbf{w}[n,k]}\end{aligned}$$

and correspondingly the Signal-to-Interference+Noise Ratio (SINR) is given by [3]:

$$SINR = \frac{\mathbf{w}^H[n,k]\mathbf{R}_d[n,k]\mathbf{w}[n,k]}{\mathbf{w}^H[n,k](\mathbf{R}_u[n,k]+\mathbf{R}_n)\mathbf{w}[n,k]}. \qquad (6)$$

Equation 3 is the basis for our initial simulations, where *perfect channel knowledge* has been assumed. Since in a real environment the receiver does not have perfect knowledge of the channel, its parameters have to be estimated, a problem which we will address in Section 4 on an OFDM symbol-by-symbol basis by means of orthogonal pilot sequences.

The Adaptive Bit-assignment Algorithm - The adaptation performed by the modem is based on the choice between a set of four modulation modes, namely 4, 2, 1 and 0 bit/subcarrier, where the latter corresponds to 'no transmission'. The modulation mode could be assigned on a subcarrier-by-subcarrier basis, but the signalling overhead of such a system would be prohibitive. Hence, we have grouped adjacent subcarriers into 'sub-bands' and assign the same modulation mode to all subcarriers in a sub-band. Note that the frequency domain channel transfer function is typically not constant across the subcarriers of a sub-band, hence the modem mode adaptation will be sub-optimal for some of the subcarriers. The Signal-to-Noise Ratio (SNR) of the subcarriers will be shown to be in most cases an effective measure for controlling the modulation assignment. The modem mode adaptation is hence achieved by calculating in the first step for each sub-band and for all four modulation modes the expected overall sub-band bit error rate (BER) by means of averaging the estimated individual subcarrier BERs. Throughout the second step of the algorithm - commencing with the lowest modulation mode in all sub-bands - in each iteration the number of bits/subcarrier of that sub-band is increased, which provides the best compromise in terms of increasing the number of expected bit errors compared to the number of additional data bits accommodated, until the target number of bits is reached.

The Channel Models - Simulations have been conducted for the indoor Wireless Asynchronous Transfer Mode (WATM) channel impulse response (CIR) of [1]. This three-path impulse response exhibits a maximal dispersion of 11 time-domain OFDM samples, with each path faded according to a Rayleigh distribution of a normalised maximal Doppler frequency of $f'_d = 1.235 \cdot 10^{-5}$, where the normalisation interval was the OFDM symbol duration. This model corresponds to the channel experienced by a mobile transmitting at a carrier frequency of 60 GHz with a sampling rate of 225 MHz and travelling at a vehicular velocity of 50 km/h. An alternative channel model, which we considered in our simulations is a Wireless Local Area Network (WLAN) model associated with a seven-path impulse response having a maximal dispersion of 32 samples. However, for this more dispersive and higher Doppler frequency channel adaptive modulation has turned out to be less effective due to its significantly increased normalised Doppler frequency of $f'_d = 3.935 \cdot 10^{-5}$ corresponding to a carrier frequency of 17 GHz, sampling rate of 20 MHz and vehicular velocity of 50 km/h.

3. SIMULATION RESULTS - PERFECT CHANNEL KNOWLEDGE

General Remarks - In our initial simulations we assumed that the receiver had perfect knowledge of all channel parameters, which enabled the estimation of the correlation matrix required by the SMI algorithm upon using Equation 3. Furthermore, we initially assumed that the receiver was capable of signalling the modulation modes to the transmitter without any additional delay. Throughout our discussions we will gradually remove the above idealistic assumptions. In all simulations we assumed a partitioning of the 512-subcarrier OFDM symbol's total bandwidth into 16 equal-sized 32-subcarrier sub-bands. This has been shown to provide a reasonable compromise between signalling overhead and performance degradation compared to a subcarrier-by-subcarrier based modulation mode assignment.

Two-Branch Maximum–Ratio Combining - Initial simulations were conducted in the absence of co-channel interference. In this scenario the SMI equations take the form of the MMSE maximum-ratio combiner, resulting in a high diversity gain even with the minimal configuration of only two reception elements. Adaptive modulation was performed on the basis of the estimated SNR of each subcarrier, which is given by Equation 5. Since due to diversity reception the dramatic fades of the channel frequency response have been mitigated, the performance advantage of adaptive modulation is more modest, as illustrated by Figure 2 for the 'transmission frame-invariant' WATM channel, for which the fading profile is kept constant for the OFDM symbol duration, in order to avoid inter-subcarrier interference. For the equivalent simulations in the 'transmission frame-invariant' WLAN channel environment we observed a more distinct performance gain due to adaptive modulation, which is justified by the higher degree of frequency selectivity introduced by the WLAN channel's seven-path impulse response.

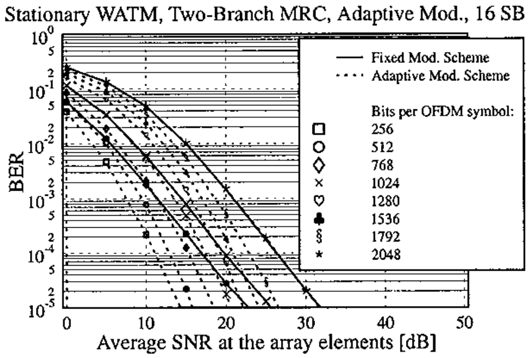

Figure 2: BER of 16-sub-band AOFDM modem with *two-branch maximum-ratio combining* in a *'frame-invariant' indoor WATM* environment, assuming *perfect channel knowledge* and *zero-delay signalling* of the modulation modes

SMI Co-Channel Interference Suppression - In these simulations we considered first of all the case of a single dominant co-channel interferer of the same signal strength as the desired user. It is well-known that if the total number of users - whose signals arrive at the antenna array - is less or equal to the number of array elements, the unwanted users are suppressed quite effectively. Hence, for our modulation adaptation requirements we can assume that $SNR \approx SINR$, which enables us to use the algorithm described in Section 2, on the basis of the SNR estimated with the aid of Equation 5. Figure 3 illustrates the impact of adaptive modulation in the WATM channel environment under the outlined conditions. At a given SNR the performance gain due to adaptive modulation decreases with an increasing bitrate, since the higher bitrate imposes a more stringent constraint on the modulation mode assignment, invoking a higher number of low-SNR subcarriers. Upon comparing Figure 3 and 4 we observe that AOFDM attains a significantly higher SNR gain in the presence of co-channel interference, than without interference. As alluded to in the previous Section this is because under co-channel interference the SMI scheme exploits most of its diversity information extracted from the antenna array for suppressing the unwanted signal components, rather than mitigating the frequency domain channel fades experienced by the wanted user. For decreasing values of the Interference-to-Noise Ratio (INR) at the antenna array output, the system performance will gradually approach the performance observed for the MRC system. In order to render our investigations more realistic in our next experiment we allow a continous, i.e. 'frame-variant' fading across the OFDM symbol duration. The system performance corresponding to this scenario is illustrated in Figure 4. At low SNRs the observed performance is identical to that recorded in Figure 3 for the 'frame-invariant' channel model, whereas at high SNRs we experience a residual BER due to inter-subcarrier interference. Again, for a low number of bits per OFDM symbol the adaptive scheme is capable of reducing the 'loading' of subcarriers with low SNR values, which are particularly impaired by inter-subcarrier interference. Hence AOFDM exhibits a BER improvement in excess of an order of magnitude. So far we have assumed

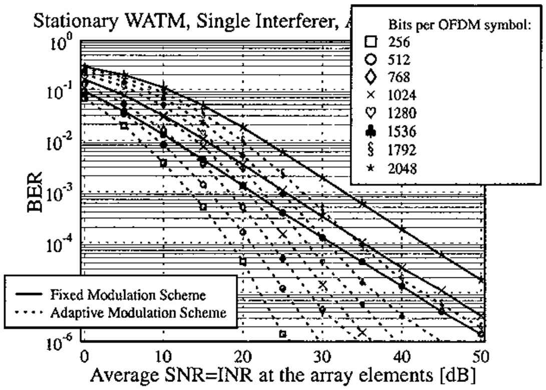

Figure 3: BER of 16-sub-band AOFDM modem with *two-branch SMI* and 2 *users* in a *'frame-invariant' indoor WATM* environment, assuming *perfect channel knowledge* and *zero-delay signalling* of the modulation modes

that the receiver is capable of instantaneously signalling the required modulation modes for the next OFDM symbol to the transmitter. This assumption cannot be maintained in practice. Here we assume a time division duplexing (TDD) system with identical transceivers at both ends of the link, which communicate with each other using adjacent up-link and down-link slots. Hence we have to account for this by incorporating an additional delay of at least one OFDM symbol, while neglecting the finite signal processing delay. Simulation results for this scenario are depicted in Figure 5. We observe that the performance gain attained by adaptive modulation is reduced compared to that associated with the zero-delay assumption in Figure 4. This could partly be compensated for by channel prediction. When employing a higher number of array elements, the performance gain achievable by adaptive modulation will mainly depend on the number of users and their signal strength. If the number of users is lower, than the number of array elements, or if the interferers are predominantly weak, the remaining degrees of freedom for influencing the array response are dedicated by the SMI scheme to providing diversity for the reception of the wanted user and hence adaptive modulation proves less effective. If the number of users exceeds the number of array elements, the system becomes incapable of suppressing the undesired users effectively, resulting in a residual BER at high SNRs due to the residual co-channel interference. Since for a relatively high number of users the residual interference exhibits Gaussian-noise like characteristics, the SINR given by Equation 6 could be a suitable measure for performing the modulation mode assignment. By contrast, for a low number of interferers it is difficult to predict the impact on the system performance analytically. A possible approach would be to use the instantaneous number of errors in each sub-band (e.g. at the output of a turbo decoder) as a basis for the modulation assignment, which constitutes our future work. Let us now consider the issues of channel parameter estimation.

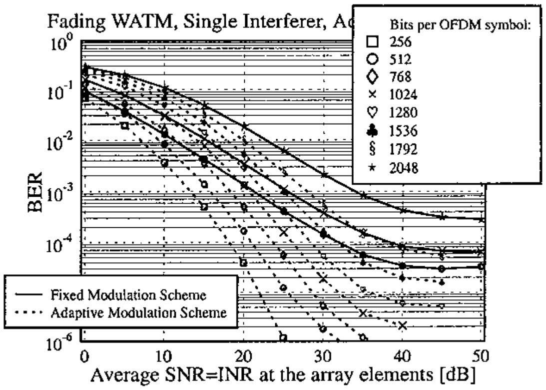

Figure 4: Performance results of Figure 3 repeated for a *fading indoor WATM* environment

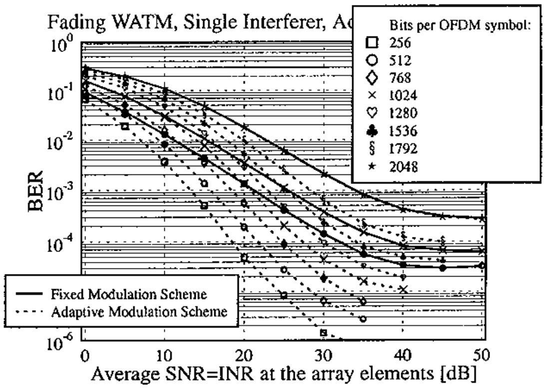

Figure 5: Performance results of Figure 4 repeated for *one OFDM symbol delayed signalling*

4. PILOT-BASED CHANNEL PARAMETER ESTIMATION

System Description - Vook and Baum [4] have proposed SMI parameter estimation for OFDM by means of orthogonal reference sequences carrying pilot slots, which are transmitted over several OFDM symbol durations. This principle can also be applied on an OFDM symbol-by-symbol basis, as required for adaptive modulation. Upon invoking the idea of pilot based channel estimation by means of sampling and low-pass interpolating the channel transfer function, we replace each single pilot subcarrier by a group of pilots, which carries a replica of the user's unique reference sequence. This is illustrated in Figure 6 for a reference sequence having a length of 4 bit, and for a pilot group distance of 16 subcarriers, which corresponds to the frequency required for sampling the WATM channel's transfer function. The corresponding 4-bit orthogonal Walsh code based reference sequences are listed in Table 1. Each of these 4

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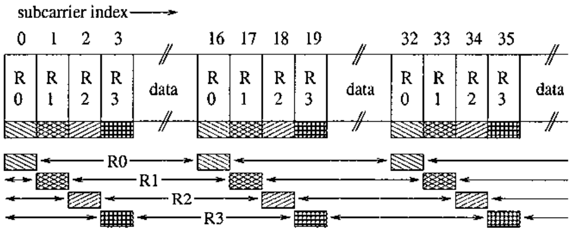

Figure 6: Pilot arrangement in each OFDM symbol for a *reference length of* 4 *bit* and a *group distance of* 16 *subcarriers*; interpolation is performed between pilots associated with the same bit position within the reference sequence

code/bit	0	1	2	3
0	1	1	1	1
1	1	1	-1	-1
2	1	-1	-1	1
3	1	-1	1	-1

Table 1: Orthogonal Walsh codes with a length of 4 bit

bits is assigned using BPSK to one of the 4 pilots in a pilot-group. The complex signal received by the m-th antenna in a pilot subcarrier at absolute index k and local index i within the reference sequence is constituted by a contribution of all users, each of which consists of the product of the Walsh code value associated with the user at bit position i of the reference sequence of Table 1 and the complex channel coefficient between the transmitter and the m-th antenna. MMSE lowpass interpolation is performed between all pilot symbols of the same relative index i within the k-spaced pilot blocks - as seen in Figure 6 - in order to generate an interpolated estimate of the reference for each subcarrier. An estimate of the channel vector $\hat{\mathbf{H}}^{(0)}[n,k]$ and the correlation matrix $\hat{\mathbf{R}}[n,k]$ for the k-th subcarrier of the n-th OFDM symbol is then given by [2–4]:

$$\hat{\mathbf{H}}^{(0)}[n,k] = \frac{1}{N}\sum_{i=0}^{N-1} r^{(0)^*}(i)\mathbf{x}_{LP}[n,k](i) \tag{7}$$

$$\hat{\mathbf{R}}[n,k] = \frac{1}{N}\sum_{i=0}^{N-1} \mathbf{x}_{LP}[n,k](i)\mathbf{x}_{LP}^{H}[n,k](i), \tag{8}$$

where $r^{(0)}(i)$ denotes the i-th value of the reference sequence associated with the desired user, $\mathbf{x}_{\mathbf{LP}}[n,k](i)$ represents the low-pass interpolated received signal at sequence position i and N denotes the total reference length.

Simulation Results - The performance of this scheme is characterised by the simulation results presented in Figure 7. Compared to the results presented in Figure 5 for 'perfect channel knowledge', in Figure 7 we observe that besides the reduced range of supported bitrates there is an additional performance degradation, which is closely related to the choice of the reference length. Specifically, there is a reduction in the number of useful data subcarriers due to the pilot overhead, which reduces the 'adaptively' exploitable diversity potential. Secondly, a relatively short reference sequence results in a limited accuracy of the estimated channel parameters - an effect which can be partly compensated for by a technique referred to as diagonal loading [6]. However, the effect of short reference sequences becomes obvious for a higher number of antenna elements, since more signal samples are required, in order to yield a reliable estimate of the correlation matrix. Hence our scheme proposed here is attractive for a scenario having 2-3 reception elements, where the interference is due to 1-2 dominant interferers and an additional Gaussian noise like contribution of background interferers, which renders the SINR of Equation 6 to be an effective measure of channel quality. **In conclusion** the proposed adaptive array assisted AOFDM scheme resulted typically in an order of magnitude BER reduction due to employing adaptive modulation.

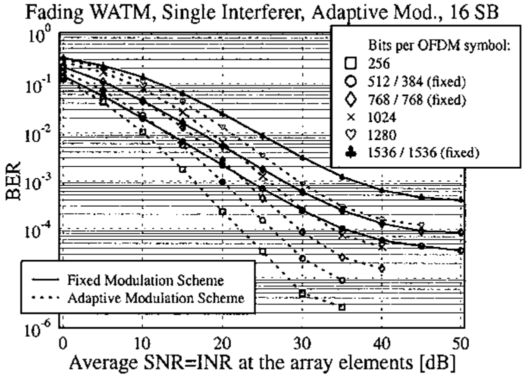

Figure 7: BER of 16-sub-band adaptive OFDM modem with *two-branch SMI* and 2 *users* in a *fading indoor WATM* environment, with *pilot based channel parameter estimation* and *one OFDM symbol delayed signalling* of the modulation assignment using a *diagonal loading* of $\gamma = 1.0$

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