An Adaptive Power and Bit Allocation Algorithm for Multiple User MIMO OFDM System Employing Zero-Forcing Multi-user Detection

Peerapong Uthansakul and Marek E. Bialkowski
School of Information Technology and Electrical Engineering, The University of Queensland
E-mail: ppg@itee.uq.edu.au and meb@itee.uq.edu.au

Abstract

This paper describes an adaptive algorithm for power and bit allocations in a multiple user Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing (MIMO OFDM) system operating in a frequency selective fading channel. The zero forcing (ZF) technique is applied to accomplish multi user detection (MUD). The proposed adaptive algorithm employs a Lagrange multiplier method, which provides an optimal solution for power and bit allocations in one step. This is of considerable advantage in comparison with alternative algorithms, such as the greedy algorithm, that require time-consuming iterative procedures. The simulation results for both perfect and partial channel state information (CSI) available to transmitter show that the algorithm operates successfully in multiple user access scenarios without scarifying power and diversity gain.

1. Introduction

Recent years have seen increasing attempts to extend broadband multimedia services to mobile wireless networks. As the result of these efforts the MIMO OFDM system, being the combination of Multiple Input Multiple Output (MIMO) diversity techniques [1]-[2] and Orthogonal Frequency Division Multiplex (OFDM) technique [3], is envisaged as a future wireless system meeting broadband requirements.

In order to further enhance the performance of the MIMO OFDM system, an adaptive scheme with respect to power allocation [4], [5], modulation [6], beam forming [7], subcarrier allocation [8]-[9] and transmission data rate [10] can be applied. Practical implementations of such adaptive techniques are under way and concern HIPERLAN II [11], cdma2000, and GPRS-136 [6].

The initial work on adaptive techniques in relation to MIMO OFDM systems was reported in [7]-[9]. In order to obtain optimal subcarrier power and bit allocations the so-called greedy algorithm was applied. One has to note that this algorithm is of high computational complexity and yields a one bit optimal solution. Computationally more efficient algorithms were proposed in [12]. However, they still require an iterative procedure for their implementation, which delays obtaining an optimal solution and affects the quality of service (QOS) [13]. Therefore, of considerable interest is an adaptive algorithm which involves only a one step procedure to minimize delay in signal processing.

A Lagrange multiplier method is one of the most popular methods to obtain a one-step optimal solution for multivariate problems. An application of the Lagrange multiplier method to various wireless communication problems was demonstrated in [5], [10], [14]-[15].

In [15], a comparison between the performance of Lagrange and greedy algorithms for power and bit allocation in a single user MIMO OFDM system was presented. It was shown that the Lagrange algorithm provides much a faster execution time while leading to a similar system performance as offered by the greedy algorithm. However, no results for the multi user case were shown.

Adaptive techniques for MIMO OFDM system involving multiple user scenarios were the subject of investigations in [8]-[9], [16]-[18]. In these works, the common approach with respect to multiple users was to eliminate Multiple Access Interference (MAI). The reason for this action was to avoid solving a very complicated adaptation problem. A number of simplifying assumptions to ease the difficulty were as follows. In [9] and [16], the authors did not allow users to share the same subcarrier. As a result, there was no CCI in each subcarrier. However, this assumption led to an inefficient utilization of the available frequency spectrum. In [17], the authors proposed an orthogonal method to solve the CCI problem. This method involved a constraint on the number of antennas, which in turn led to sacrificing an antenna diversity gain. In [18], redundant OFDM symbols were used to eliminate CCI.

In this paper, a MIMO OFDM system without the above mentioned simplifying assumptions is considered. An arbitrary number of antennas at transmitter and receiver are assumed and users are allowed to share the same subcarrier. A close-form solution for adapting bit and power allocations for such a system is produced. The validity of this solution is verified via computer Monte Carlo simulations.

2. System model

2.1. Transmitter of adaptive MIMO OFDM system

The configuration of transmitter of an adaptive MIMO OFDM system available to the *k*th user is shown in Figure1. This configuration being the same for all of the *K* users includes N_T transmitting antennas and various data processing blocks. As seen in Figure 1, the tasks of adaptive modulation, power allocation and beam forming are divided into separate blocks. They require some information about the channel, which is obtained via a feedback loop from the receiver. It is assumed that the receiver knows the channel in a perfect way (for example from training sequences).

For *k*th user, it is assumed that B_k bits correspond to one OFDM symbol which also implies that B_k can be interpreted as data rate transmission with the rate of B_k bits per one symbol period. In each symbol duration, a data stream composed of B_k bits is fed into N_C parallel streams, each containing $b_{k,1}$, $b_{k,2}$, ..., $b_{k,Nc}$ bits. These data streams are modulated into a symbol sequence $s_{k,1}, s_{k,2}$, ..., $s_{k,Nc}$ to be transmitted on N_C subcarriers. Each symbol $s_{k,m}$ is scaled to a unit power and the transmitted power of each symbol is defined as $\delta_{k,m}$ for *m*th subcarrier. This operation is required to make power adjustments over the sub-carriers. In order to perform adaptive beamforming, the scaled symbols are multiplied with the basis beam $\mathbf{v}_{k,m}$, given by an $N_T\times1$ vector. At the end of the transmitter, Inverse Fast Fourier Transform (IFFT) including cyclic prefix insertion (N_{CP} subcarriers) is performed. Values of $b_{k,m}$, $s_{k,m}$, $\delta_{k,m}$ and $\mathbf{v}_{k,m}$ are adjusted by an adaptive algorithm according to the feedback channel information.

2.2. MIMO channel modeling

We assume that the investigated MIMO OFDM system operates in a frequency selective fading channel [19] whose characteristics stay the same during one OFDM symbol. The fading channel between the *i*-th transmit antenna and the *j*-th receive antenna is modeled by a discrete time baseband equivalent *L*-1 order finite impulse response (FIR) filter with filter taps $g_{k,ij}(l)$, where l = 0,1, …, *L*-1. It is assumed that the *L* taps are independent zero mean complex Gaussian random variables with variance $\sigma_g^2(l)$ and $\sigma_h^2 = \sum \sigma_g^2(l)$. The set of these variances define the power delay profile (PDP). Here, PDP is assumed to be an exponentially decaying function

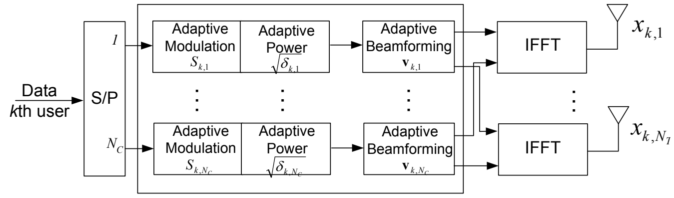

Figure 1. Transmitter of adaptive MIMO OFDM system

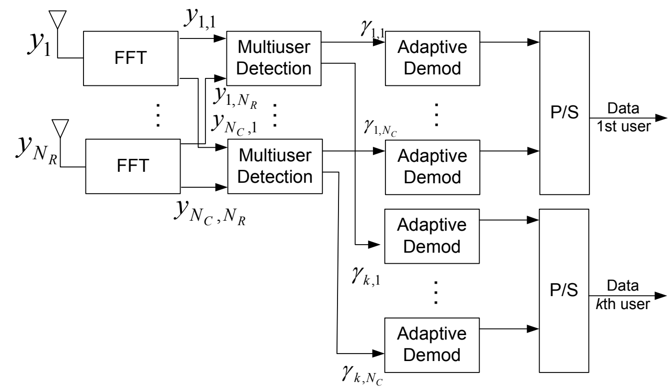

Figure 2. Receiver of adaptive MIMO OFDM system

with the root mean square delay spread defined by IEEE 802.11a standard [19]. The discrete time MIMO baseband system at the *t*th time instant for *k*th user is described by the following equation

$$\mathbf{y}(t) = \sum_{k=1}^{K} \sum_{t=1}^{L} \mathbf{G}_k(l)\mathbf{x}_k(t-l) + \mathbf{n}(t) \qquad (1)$$

where $\mathbf{y}$ (*t*) is the complex $N_R\times1$ vector representing N_R received signals, $\mathbf{G}_{\boldsymbol{k}}(l)$ is the complex $N_R\times N_T$ matrix consisting of the elements $g_{k,ij}(l)$ and independent from *k*, $\mathbf{x}_{\boldsymbol{k}}(t)$ is the complex $N_T\times1$ vector representing N_T transmitted signals and $\mathbf{n}(t)$ is the complex $N_R\times1$ vector describing N_R additive and discrete time noise at receiver. Note that the inter symbol interference (ISI) can be eliminated by choosing $L \leq N_C+N_{CP}+1$. As a result, the channel response between transmitter and receiver is assumed to be flat on each subcarrier and defined by the complex $N_R\times N_T$ matrices $\mathbf{H}_{k,m}$, where *m* denotes the subcarrier number of *k*th user.

2.3. Receiver of adaptive MIMO OFDM system

The configuration of the receiver of the investigated adaptive MIMO OFDM system is shown in Figure 2. It includes N_R antennas and data processing blocks similar to those in the transmitter of Figure1. Assuming perfect frequency synchronization, time synchronization and availability of tracking pilot subcarrier [19], the received signals of *m*th subcarrier is expressed as (2).

$$\mathbf{y}_m = \sum_{k=1}^{K} \mathbf{H}_{k,m}\mathbf{v}_{k,m}\sqrt{\delta_{k,m}}\, s_{k,m} + \mathbf{n}_m \qquad (2)$$

where $\mathbf{y}_m$ is the complex $N_R \times 1$ vector representing a received signals $y_{m,1}$, $y_{m,2}$, …, $y_{m,Nc}$ and $\mathbf{n}_m$ is the complex $N_R \times 1$ vector with variance N_0.

In the undertaken investigations, it is assumed that the CSI is perfectly known to the receiver. The transmitter receives this information using feedback from receiver. Two cases are considered, when perfect and imperfect feedback between receiver and transmitter sites, are assumed.

2.3.1. Perfect CSI at Transmitter. The adaptive process is carried out according to the instantaneous CSI. For the system with time division duplex, this assumption can be tolerable [8]. By applying the singular value decomposition (SVD) technique to channel matrix ($\mathbf{H}_{k,m} = \mathbf{U}_{k,m}\mathbf{\Lambda}_{k,m}\mathbf{V}_{k,m}^{\dagger}$), the transmitter can select the basis beam vector $\mathbf{v}_{k,m}$ along with the vector $\mathbf{u}_{k,m}$ to achieve the maximum eigenvalue $\lambda_{k,m}^{\max}$. Note that $(\cdot)^{\dagger}$ is the conjugate and transpose operation (Hermitian operation). Therefore, the received signal at mth subcarrier is given as

$$\mathbf{y}'_m = \mathbf{U}_m^{\dagger}\mathbf{U}_m\mathbf{\Lambda}_m\mathbf{s}_m + \mathbf{U}_m^{\dagger}\mathbf{n}_m \quad (3)$$

where $\mathbf{U}_{\mathrm{m}}$ is the $N_R \times K$ matrix of $[\mathbf{u}_{1,m}, \mathbf{u}_{2,m}, \ldots \mathbf{u}_{K,m}]$, $\mathbf{\Lambda}_m$ is the $K \times K$ diagonal matrix of $\lambda_{k,m}^{\max}$ and $\mathbf{s}_{\mathrm{m}}$ is the $K \times 1$ vector of $\sqrt{\delta_{k,m}}s_{k,m}$.

In this work, Zero Forcing (ZF) technique is chosen for Multi User Detection (MUD). This is the most popular method and easy to implement. By applying ZF technique, the decision can be expressed as

$$\mathbf{y}''_m = \mathbf{\Lambda}_m\mathbf{s}_m + (\mathbf{U}_m^{\dagger}\mathbf{U}_m)^{-1}\mathbf{U}_m^{\dagger}\mathbf{n}_m \quad (4.1)$$

$$y''_{k,m} = \lambda_{k,m}^{\max}\sqrt{\delta_{k,m}}s_{k,m} + \mathbf{d}_{k,m}\mathbf{U}_m^{\dagger}\mathbf{n}_m \quad (4.2)$$

where $(\mathbf{U}_m^{\dagger}\mathbf{U}_m)^{-1} = [\mathbf{d}_{1,m}\ \mathbf{d}_{2,m}\ \ldots\ \mathbf{d}_{K,m}]^T$, $(\cdot)^T$ is the transpose operation. To consider only the kth user in mth subcarrier, the hard decision can be achieved by $y''_{k,m}$ and then the SNR can be written in (5).

$$\mathrm{SNR}_{k,m} = \frac{(\lambda_{k,m}^{\max})^2\delta_m}{c_{k,m}N_0} \quad (5)$$

where $c_{k,m} = \left\|\mathbf{d}_{k,m}\mathbf{U}_m^{\dagger}\right\|_F^2$ is the spatial correlation between kth user and the other users,. Note that $\|(\cdot)\|_F$ denotes the Frobenius norm. This spatial correlation implies the strength of CCI in the system. As observed in (5), this factor is independent from power allocation, making the optimization problem more feasible to solve.

2.3.2. Partial CSI at Transmitter. In practice, the availability of perfect CSI at transmitter is difficult to achieve. Therefore the assumption of partial CSI is more meaningful to consider. Here, the concept of channel mean feedback, as introduced in [7], is adopted for the partial CSI model. Using this concept, the channel information of mth subcarrier at the transmitter is modeled as $\widetilde{\mathbf{H}}_{k,m}$ with the mean value of $\overline{\mathbf{H}}_{k,m}$ and the covariance matrix of $N_R\sigma_{k,m}^2\mathbf{I}_{N_T}$. $\overline{\mathbf{H}}_{k,m}$ is the conditional mean of $\widetilde{\mathbf{H}}_{k,m}$ when the feedback channel information $\mathbf{H}_{k,m,f}$ is arrived at transmitter. Therefore $\widetilde{\mathbf{H}}_{k,m}$ is a delayed version of $\mathbf{H}_{k,m,f}$ characterized by the correlation coefficient from Jakes' model: $\rho_k = J_0(2\pi f_d\tau)$, where $J_0(.)$ is the 0th order Bessel function, f_d is the maximum Doppler frequency and τ is the feedback delay. When the channel information is fed back to the transmitter with delay τ but without errors, the channel realization that transmitter obtains is $\overline{\mathbf{H}}_{k,m} = \rho_k\mathbf{H}_{k,m,f}$ and the variance is $\widetilde{\sigma}_{k,m}^2 = (1-|\rho_k|^2)\sigma_h^2$. Therefore at transmitter the channel matrix $\mathbf{H}_{k,m}$ can be modeled as $\widetilde{\mathbf{H}}_{k,m}$ as shown in (6).

$$\widetilde{\mathbf{H}}_{k,m} = \overline{\mathbf{H}}_{k,m} + \mathbf{H}_{k,m}^W \quad (6.1)$$

$$E\{\widetilde{\mathbf{H}}_{k,m}\widetilde{\mathbf{H}}_{k,m}^{\dagger}\} = \overline{\mathbf{U}}_{k,m}(\overline{\mathbf{\Lambda}}_{k,m} + N_R(1-\rho^2)\sigma_h^2\mathbf{I})\overline{\mathbf{U}}_{k,m}^{\dagger} \quad (6.2)$$

By applying this concept into (2) and selecting the basis beam vector $\mathbf{v}_{k,m}$ along with the vector $\overline{\mathbf{u}}_{k,m}$ to achieve the maximum eigenvalue $\overline{\lambda}_{k,m}^{\max}$, one can rewrite the received signal in (3) as (7).

$$\mathbf{y}'_m = \overline{\mathbf{U}}_m^{\dagger}\overline{\mathbf{U}}_m\overline{\mathbf{\Lambda}}_m\mathbf{s}_m + \overline{\mathbf{U}}_m^{\dagger}\mathbf{W}_m\mathbf{s}_m + \overline{\mathbf{U}}_m^{\dagger}\mathbf{n}_m \quad (7)$$

where $\mathbf{W}_{\mathrm{m}}$ is the $N_R \times K$ matrix of $\mathbf{H}_{k,m}^W\mathbf{v}_{k,m}$.

After applying ZF technique, the solution can be expressed as given in (8)

$$y''_{k,m} = \overline{\lambda}_{k,m}^{\max}\sqrt{\delta_{k,m}}s_{k,m} + \overline{\mathbf{d}}_{k,m}\overline{\mathbf{U}}_m^{\dagger}\mathbf{W}_m\mathbf{s}_m + \overline{\mathbf{d}}_{k,m}\overline{\mathbf{U}}_m^{\dagger}\mathbf{n}_m \quad (8)$$

By considering only the kth user in mth subcarrier, the hard decision can be achieved by $y''_{k,m}$ and thus the SNR can be written in (9).

$$\mathrm{SNR}_{k,m} = \frac{E\{|\overline{\lambda}_{k,m}^{\max}\sqrt{\delta_{k,m}}s_{k,m} + \overline{\mathbf{d}}_{k,m}\overline{\mathbf{U}}_m^{\dagger}\mathbf{W}_m\mathbf{s}_m|^2\}}{E\{|\overline{\mathbf{d}}_{k,m}\overline{\mathbf{U}}_m^{\dagger}\mathbf{n}_m|^2\}} = \frac{(\rho_k^2(\lambda_{k,m}^{\max})^2 + N_R(1-\rho_k^2)\sigma_h^2)\delta_m}{\overline{c}_{k,m}N_0} \quad (9)$$

2.3.3. Bit error rate approximation. To simplify the task of evaluating bit error rate (BER), a unified expression of approximate BER [20] for QAM modulation is given in (10).

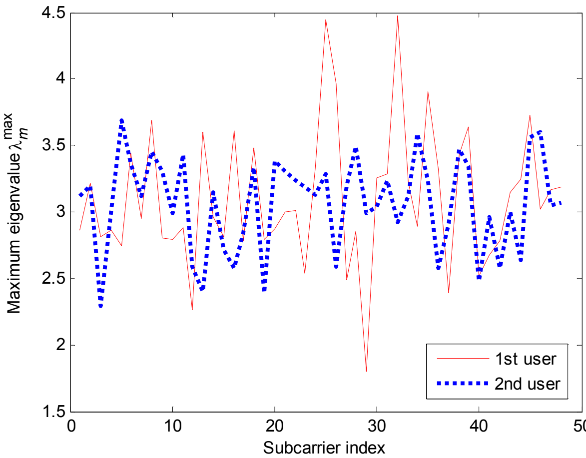

Figure 3. The maximum eigenvalue $\lambda_{k,m}^{\max}$ versus subcarrier index for multiple users, K = 2, N_C = 48, N_R=N_T=4.

$$\mathrm{BER}_{k,m} \approx 0.2 \exp(-g_{k,m}(b_{k,m})\mathrm{SNR}_{k,m}) \quad (10)$$

where the constant $g_{k,m}(b_{k,m})$ depends on whether the chosen constellation is rectangular or square QAM:

$$g_{k,m}(b_{k,m}) = \begin{cases} \dfrac{6}{5 \cdot 2^{b_{k,m}} - 4} & b_{k,m} = 1,3,5,... \\ \dfrac{6}{4 \cdot 2^{b_{k,m}} - 4} & b_{k,m} = 2,4,6,... \end{cases}$$

3. Adaptive algorithms

An adaptive algorithm requires an objective function and constraining conditions to optimize the performance of MIMO OFDM system. As seen in (5) (9) and (10), there are three main parameters apart from the knowledge of channel information which directly influence the system performance. These are BER ($\mathrm{BER}_{k,m}$), transmitted SNR ($\delta_{k,m}/N_0$) and a number of loaded bits ($b_{k,m}$). In this paper, the aim of optimization is to minimize the total transmitted power (P_T) while keeping a constant data rate transmission (B_k). Here, the guarantee BER is defined by the target Bit Error Rate ($\mathrm{BER}_{\mathrm{Target}}$).

Using the above assumptions, the optimization problem can be formulated as follows:

$$\arg\min_{b_{k,m}} \sum_{k=1}^{K}\sum_{m=1}^{N_C} \delta_{k,m} \quad (11.1)$$

$$\text{subject to}: \sum_{m=1}^{N_C} b_{k,m} = B_k \quad \forall k$$
$$\delta_{k,m} > 0 \quad (11.2)$$
$$b_{k,m} > 0$$
$$\mathrm{BER}_{k,m} = \mathrm{BER}_{\mathrm{Target}}$$

For this algorithm the optimization process is defined by equation (12)

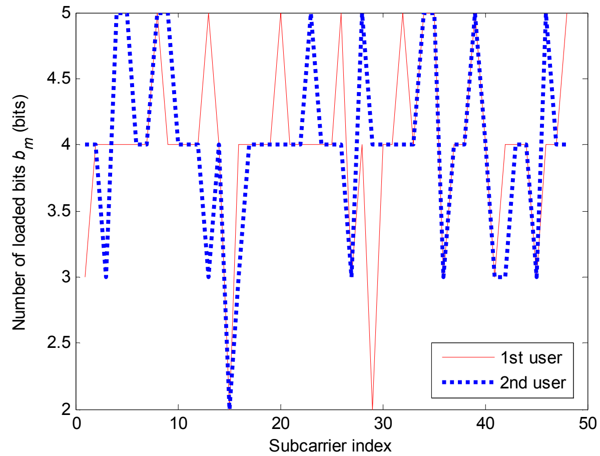

Figure 4. Number of loaded bits $b_{k,m}$ (bits) versus subcarrier index for multiple users, K = 2, N_C = 48, B_k = 24 bytes, N_R=N_T=4 and $\mathrm{BER}_{\mathrm{target}} = 10^{-3}$.

$$\frac{\partial}{\partial b_{k,m}}\left(\sum_k\sum_m \delta_{k,m} + \sum_k \mu_k\left(\sum_m b_{k,m} - B_k\right)\right) = 0 \quad (12)$$

where μ_k , being the constant value, is a Lagrange multiplier factor. Under the constraining conditions the solution is expressed in (13).

$$b_{k,m} = \frac{1}{N_C}\left\{B_k + \log_2\left(\frac{\left(\left(\lambda_{k,m}^{\max}\right)^2 / c_{k,m}\right)^{N_C}}{\prod_{m'=1}^{N_C}\left(\lambda_{k,m'}^{\max}\right)^2 / c_{k,m'}}\right)\right\} \quad (13)$$

From (13), it can be noticed that the optimal loaded bits for all subcarriers can be obtained by performing only one-step formula calculations. However, as $b_{k,m}$ has to be an integer number, the following refinement is necessary:

1) Change $b_{k,m}$ to be the nearest integer.

2) Find bit remaining (or overloading): $B_{k,rem} = B_k - \sum b_{k,m}$

3) Add (or delete) one bit from $B_{k,rem}$ subcarriers with respect to their maximum eigenvalue $\lambda_{k,m}^{\max}$ in decreasing order.

It can be noticed that the solution using the Lagrange algorithm does not require any iterations. This makes this algorithm very fast, which is an attractive feature from the point of view of high data rate transmission system. By assuming no limitation of computational processing power, it was shown in [15] that this algorithm is about B_k faster than the iterative greedy algorithm.

4. Simulation results and discussion

The performances of the above described adaptive algorithm are investigated by using Monte Carlo simulations in MATLAB. In simulations one OFDM

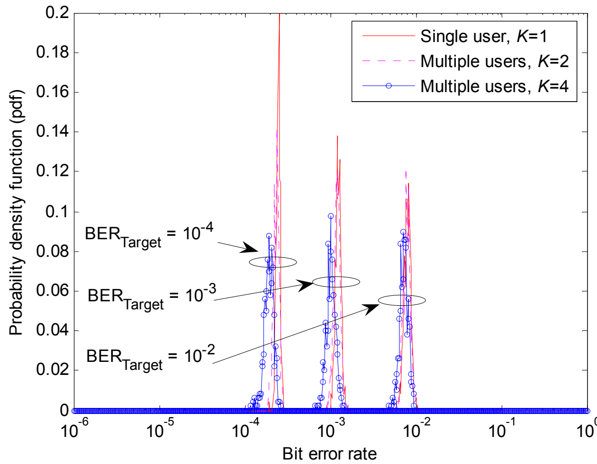

Figure 5. Probability density function (pdf) of bit error rate per user for N_C = 48, ρ = 1 (Perfect CSI), B_k = 24 bytes and N_R=N_T=4.

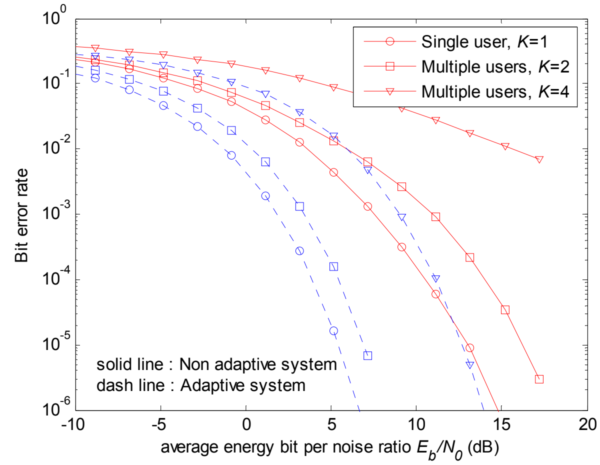

Figure 6. Bit error rate vs. average energy bit per noise ratio E_b/N_0 (dB) for N_C = 48, ρ = 1 (Perfect CSI), B_k = 24 bytes and N_R=N_T=4.

symbol with 64 subcarriers and N_C = 48 data subcarriers [21] is assumed. Evaluation concerns over 2,000 OFDM symbols sent for each realization of the mean feedback channel. The presented results concern an averaging of 1,000 channel realizations. The PDP of the frequency selective fading channel is modeled by an exponential function with rms delay spread of 250 ns with 32 taps (L). All channels are assumed to be Rayleigh fading channels. The results are simulated with the fixed bit rate transmission of 24 bytes (B_k=192 bits) per one OFDM symbol.

4.1. Bit allocations

Figure 3 shows the characteristic of maximum eigenvalue $\lambda_{k,m}^{\max}$ of a 4x4 MIMO system over subcarrier frequency; N_C = 48 when two users are present in the system. This eigenvalue is evaluated at transmitter during the adaptive process of bit allocations. It can be seen in Figure3 that the maximum eigenvalue depends on the individual user.

Figure 4 shows the number of loaded bits b_m versus subcarrier index for N_C = 48, B_k = 24 bytes, BER_{target} = 10^{-3} and N_R=N_T=4 when two users are present in the system. The adaptive algorithm tries to allocate loaded bits following the minimum power in the system. It can be observed that the algorithm attempts to find an optimal solution for each user. Note that the total number of loaded bits for the users is equal to B_k while for the non-adaptive system each subcarrier is equally allocated with 4 bits.

4.2. Probability density function of BER

Figure 5 shows the probability density function (pdf) of bit error rate for perfect CSI (ρ = 1), N_C = 48, B_k = 24 bytes, N_R=N_T=4 and BER_{target} = 10^{-2}, 10^{-3}, 10^{-4}. As observed in Figure 5, the pdf distribution of any users considering the same BER target are similar and attached around the target. These results show the success of the proposed adaptive process for multiple users because the proper power and bit allocations have been correctly assigned to achieve the desired BER.

4.3. BER performance of perfect and partial CSI

Figure 6 presents the BER performance for the case of perfect CSI (ρ = 1) for a different number of users. It is clearly seen that no matter what number of users is assumed, the adaptive system outperforms the non adaptive system. For instance, when K = 2, the adaptive system requires only 3 dB for Eo/No to achieve BER at 10^{-3} while the non adaptive system has needs 11 dB. This trend is valid for the other presented numbers of users. The energy bit used in the adaptive system for two users is much lower than for a single user in the non adaptive system. It means that for a small number of users, the adaptive system shows benefits in terms of BER and user capacity.

Figure 7 present the BER performance comparison between perfect and partial CSI for single user respectively. As expected, the performance gets poorer when the quality of feedback worsens (ρ is lower).

5. Conclusion

In this paper an adaptive algorithm for bit and power allocations in a multiple user Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing

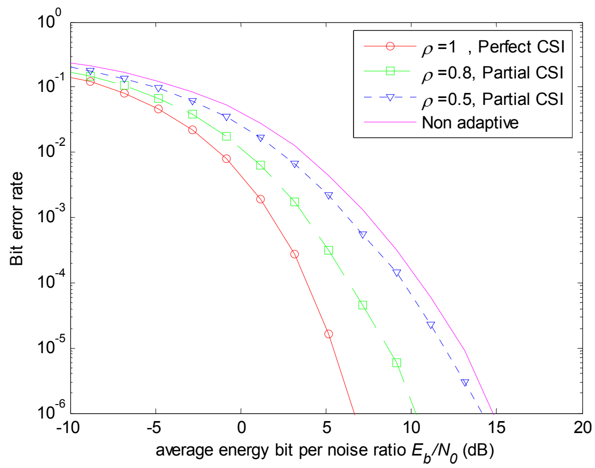

Figure 7. Bit error rate vs. average energy bit per noise ratio E_b/N_0 (dB) for single user, $K = 1$, $N_C = 48$, $B_k = 24$ bytes and $N_R=N_T=4$.

(MIMO OFDM) system operating with in a frequency selective fading channel has been described. The close-form solution for allocating loaded bits according to an assumed BER has been presented. The performances of the adaptive and non adaptive MIMO OFDM systems have been compared via Monte Carlo simulations. It has been shown that the adaptive algorithm leads a system with superior performance. The presented adaptive algorithm involves a one step procedure and thus is attractive for practical implementation because of a short execution time.

6. Acknowledgment

The authors acknowledge the financial support of the Australian Research Council via Grant DP0450118.

7. References

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas", Wireless Personal Communications, vol. 6, no. 3, pp. 311-335, Mar. 1998.

[2] D. Gesbert, M. Shafi, D. Shiu, P. J. Smith and A. Naguib, "From theory to practice: an overview of MIMO space-time coded wireless system," IEEE J. Select. Areas Commun., vol. 21, pp. 281-302, Apr. 2003.

[3] G. L. Stuber, J. R. Barry, S. W. Mclaughlin, Y. Li, M. A. Ingram and T. G. Pratt, "Broadband MIMO-OFDM wireless communications," Proc. IEEE, vol. 92, pp. 271-294, Feb. 2004.

[4] A. J. Goldsmith, S. A. Jafar, N. Jindal and S. Vishwanath, "Capacity limits of MIMO channels", IEEE J. Select. Areas Commun., vol. 21, pp. 684-702, Jun. 2003.

[5] Kai-Kit Wong, R.D. Murch, and K.B. Letaief, "Optimizing time and space MIMO antenna system for frequency selective fading channels," IEEE J. Select. Areas Commun., vol. 19, pp. 1395-1407, Jul. 2001.

[6] S. Catreux and V. Erceg, "Adaptive modulation and MIMO coding for broadband wireless data networks," IEEE Commun. Mag., pp. 108-115, Jun. 2002.

[7] P. Xia, S. Zhou and G. B. Giannakis, "Adaptive MIMO-OFDM based on partial channel state information," IEEE Trans. Signal Processing, vol. 52, pp. 202-213, Jan. 2004.

[8] Y. J. Zhang and K. B. Letaief, "An efficient resource-allocation scheme for spatial multiuser access in MIMO/OFDM systems," IEEE Trans. Commun., vol. 53, pp. 107-116, Jan. 2005.

[9] Z. Hu, G. Zhu, Y. Xia and G. Liu, "Multiuser subcarrier and bit allocation for MIMO-OFDM systems with perfect and partial channel information," Proc. IEEE WCNC, 2004, pp. 1188-1193.

[10] P. Uthansakul and M.E. Bialkowski, "Adaptive Subcarrier Technique for Mixed Low and High Data Rate in OFDM-DS-CDMA System", Proc. DSPCS03, Dec. 2003, vol.1, pp. 276-280.

[11] ETSI, "Broadband radio access networks (BRAN); HIPERLAN type2; physical layer," Technical Specification, ETSI 101 475 v1.3.1, Dec. 2001.

[12] D. Hughes-Hartogs, "Ensemble modem structure for imperfect transmission media," U.S. Patents 4,679,227 (Jul. 7, 1987); 4,731,816 (Mar. 15, 1988); 4,833,706 (May 23, 1989).

[13] Dapeng Wu and R. Negi, "Effective capacity: a wireless link model for support of quality of service," IEEE Trans. Wireless Commun., vol. 2, pp. 630 - 643, Jul. 2003.

[14] P. Uthansakul and M.E. Bialkowski, "Optimizing signal transmission in a MIMO system operating in Rayleigh and Ricean Fading Channels", Proc. ISAP04, Aug. 2004, vol.1, pp. 325-238.

[15] P. Uthansakul and M.E. Bialkowski, "Performance Comparisons between Greedy and Lagrange Algorithms in Adaptive MIMO MC-CDMA Systems," to appear in Proc. IEEE APCC05, Perth, Oct. 2005.

[16] Z. Hu, G. Zhu, Y. Xia and G. Liu, "Adaptive subcarrier and bit allocation for multiuser MIMO-OFDM transmission," Proc. IEEE VTC04, vol. 2, May 2004, pp. 779 – 783.

[17] J. Duplicy, J. Louveaux, and L. Vandendorpe, "Interference-Free Multi-User MIMO-OFDM," Proc. IEEE ICASSP05, vol. 3, Mar. 2005, pp. 1149 – 1152.

[18] A. Nallanathan, and Q. S. Sen, "Adaptive channel estimation and interference cancellation in space-time coded OFDM systems," Proc. IEEE VTC04, vol. 3, May 2004, pp. 1760 – 1764.

[19] A. V. Zelst and T. C. W. Schenk, "Implementation of a MIMO OFDM based wireless LAN system," IEEE Trans. Signal Processing, vol. 52, pp. 483-494, Feb. 2004.

[20] S. Zhou and G. B. Giannakis, "Adaptive modulation for multi-antenna transmissions with channel mean feedback," Proc. IEEE ICC, 2003, vol. 4, pp. 2281-2285.

[21] IEEE 802.11a Stand., ISO/IEC 8802-11:1999/Amd 1:2000(E).