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Adaptive Bit and Power Allocation for Indoor Wireless Multicarrier Systems

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Abstract

We propose an adaptive bit and power allocation algorithm for indoor wireless systems employing multicarrier modulation. The proposed scheme maximizes throughput via an incremental allocation algorithm while operating under a maximum mean bit error constraint. Unlike other bit allocation algorithms, which allocate a continuous distribution of bits followed by quantization, the proposed algorithm allocates a discrete distribution of bits. Moreover, the proposed algorithm employs a stricter subband power constraint to limit the interference to other users and satisfy government regulatory requirements, unlike other algorithms which only employ a total power constraint. Finally, the assumption of flat subchannels is dropped, thus a subcarrier minimum mean-squared error equalizer is applied to the case of orthogonal frequency division multiplexing systems employing a cyclic prefix. The performance of the proposed system is evaluated in terms of throughput and bit allocation and compared with an IEEE 802.11a-compliant system. The results show that the proposed system outperforms the IEEE 802.11a-compliant system when transmitting at lower signal-to-noise ratios. Furthermore, the benefits of power allocation are noticeable at low signal-to-noise ratios.

I. Introduction

The development of high speed wireless networks over the past several years has resulted in the implementation of systems which are capable of transmitting at data rates of up to 54 megabits per second (Mb/s) [1]. Although much work has gone into making these systems reliable, robust in fading channels, and spectrally efficient when transmitting at high data rates, several problems still need to be addressed. In this paper we approach the problem of a frequency-selective fading channel by using adaptive bit and power allocation in multicarrier systems.

In multicarrier modulation, data is transmitted in parallel subcarriers at a lower data rate than the serial input and output of the system. This effectively transforms the frequency selective fading channel into a collection of flat fading subchannels. An efficient version of multicarrier modulation is orthogonal frequency division multiplexing (OFDM), which has no intersymbol interference (ISI) when a sufficiently long cyclic prefix is used. As a result, many wireless local area network (WLAN) standards, such as IEEE 802.11a [1] and HIPERLAN/2 [2], use OFDM systems at the core of their design.

Conventional wireless OFDM systems uses a fixed signal constellation size across all subcarriers. Their overall error probabilities are dominated by the subcarriers with the worst performance.

One solution to this problem is adaptive bit and power allocation, where the signal constellation size and power distribution across all the subcarriers vary according to the estimated channel conditions in order to minimize the overall error probability. In Kalet [3], Chow et al. [4], Fischer & Huber [5], Hughes-Hartog [6], and Leke & Cioffi [7], the power and bit allocation are optimized in order to either achieve a maximum bit rate for a given probability of error or to minimize the probability of error given a target bit rate; the power level of each subcarrier sums up to a constant total power while the bit allocation can be non-integer with no maximum limit on the constellation size. On the other hand, in the work by Schmidt & Kammeyer [8], Czylwik [9], and Keller & Hanzo [10], adaptive modulation is used, where the subcarriers are adaptively modulated with a fixed number of signal constellation sizes. Although these methods either offer low complexity or near-optimal bit allocations, none offer a balance between these two criteria. Furthermore, none of these algorithms impose practical constraints on the power allocation that meet regulatory requirements. In this paper, we pro-

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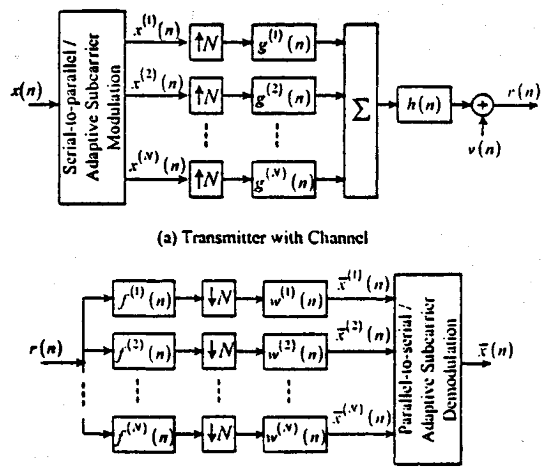
pose an adaptive bit and power allocation algorithm for wireless multicarrier systems in order to enhance system throughput while satisfying a mean bit error rate constraint. The bit allocation algorithm is performed incrementally while the power allocation satisfies a subband power constraint. To enhance system performance, especially when the number of subcarriers is insufficient to result in flat subchannels, we employ minimum mean squared error equalizers to each subcarrier and adaptively allocate taps to them based on channel conditions.

This paper is organized as follows. In Section II, an overview of multicarrier systems is presented, especially with details on orthogonal frequency division multiplexing (OFDM) systems employing cyclic prefixes. The proposed bit and power allocation algorithms are outlined in Section III. In Section IV, the design of the optimal subcarrier MMSE equalizers for OFDM systems employing cyclic prefixes and a description of the equalizer tap allocation algorithm are presented. Section V presents the results of the proposed bit allocation algorithm, bit and power allocation algorithm, and equalizer tap allocation algorithm. Finally, a summary of this work with some concluding remarks are included in Sections VI.

II. Multicarrier Modulation

The general setup for an adaptive multicarrier modulation (MCM) system is shown in Fig. 1. An MCM system divides the input symbol stream into N parallel streams, each having a larger symbol period and lower bandwidth relative to the input. In the case of adaptive MCM, the high data rate input, $x(n)$, is split into N streams with different data rates and employing different modulation schemes. Each of these parallel streams is then used to modulate a carrier using a basis function $g^{(k)}(n)$, $1 \leq k \leq N$. The modulated streams are summed together and transmitted across the channel, where they experience the effects of multipath propagation as well as noise. The received signal, $r(n)$, is decomposed into the N subcarriers using basis functions $f^{(k)}(n)$, $1 \leq k \leq N$. The subcarrier equalizers $w^{(k)}(n)$, $1 \leq k \leq N$, are then applied to each of the received parallel streams and the result is demodulated and multiplexed together to form the received symbol stream.

Two examples of MCM systems are orthogonal frequency division multiplexing (OFDM) and filter bank multicarrier (FB-MC) systems. In OFDM systems, the discrete Fourier transform (DFT) and the inverse DFT (IDFT) are employed as basis functions. Although efficiently implemented using the fast Fourier transform (FFT) and the inverse FFT (IFFT), the basis functions in OFDM systems possess poor spectral selectivity, thus cyclic prefixes are employed to remedy the situation. In FB-MC systems, the basis functions can be designed to be more spectrally selective than the OFDM basis functions, thus removing the need for a cyclic prefix. This type of MCM system and the application of adaptive allocation was studied in [11].



(a) Transmitter with Channel

(a) Receiver

Fig. 1 A schematic of the adaptive wireless multicarrier data transmission system

III. Bit & Power Allocation Algorithms

In this section, the proposed bit and power allocation algorithms and its advantages over other allocations algorithms are presented. Before continuing, we briefly perform a literature survey to define the current state-of-the-art.

A. Existing Bit & Power Allocation Algorithms

One of the first bit and power allocation algorithms for multicarrier systems was developed by Hughes-Hartog [6]. In this algorithm, the incremental energy required to transmit one additional bit is computed for each of the subcarriers. The subcarrier that requires the least incremental energy is then allocated that bit and the process is repeated as long as either the total power or aggregate bit error rate constraints are not violated.

The allocation algorithm of Chow, Cioffi, and Bingham [4] makes use of an approximation for the Shannon channel capacity to compute the bit allocation across all the subcarriers. Specifically, they calculate the number of bits for subcarrier i using

$$b(i) = \frac{1}{2}\log_2\left(1 + \frac{\text{SNR}(i)}{\Gamma}\right) \quad (1)$$

where Γ is the SNR gap, representing how far the system is from achieving the Shannon capacity for a specific BER [12], and SNR(i) is the SNR of subcarrier i. Assuming equal energy across all used subcarriers, the value for system performance margin, γ_{margin}, is iteratively sought after until either the target bit rate is satisfied or the maximum number of iterations have been performed, in which case the allocation is forced to the target bit rate using a suboptimal loop. Finally, the transmission power levels are adjusted in order to achieve the same BER per used subcarrier.

In the allocation algorithm by Fischer and Huber [5], the objective is to distribute bits and power across the subcarriers in order to minimize the error probability on each subcarrier. Using the closed-form expressions for the symbol error probabilities for QAM modulation, the algorithm iteratively distributes the bits and power until the probability of error on all subcarriers are equivalent, subject to a total rate and total power constraint.

The allocation algorithm presented by Leke and Cioffi [7] assigns energy to different subcarriers in order to maximize the data rate for a given margin. First, a sort and search is performed in order to find which subcarriers should be left on while others shut off. Second, the energy is distributed either equally or via *water-filling*. Finally, the bits allocated to each subcarrier is calculated using the approximation for the Shannon channel capacity used in [4].

B. Proposed Bit Allocation Algorithm

The guiding principle behind the proposed bit allocation algorithm is to ensure the mean BER is below a specified threshold, $\text{BER}_{\text{Thres}}$, while maximizing throughput. The proposed algorithm redistributes the bits across all the subcarriers while constrained by the $\text{BER}_{\text{Thres}}$ criterion and a subcarrier bit allocation constraint. This algorithm is an improvement over other algorithms since it does not allocate a continuous distribution of bits which is then quantized [3–5, 7].

To compute the probability of bit error for all subcarriers, given that the channel conditions are known at the transmitter, closed-form expressions are employed. For instance, the probability of bit error for BPSK is given by [13]

$$P_{b,\text{BPSK}}(\gamma) = Q\left(\sqrt{2\gamma}\right) \tag{2}$$

while the probability of symbol error for QPSK ($M = 4$), rectangular 16-QAM ($M = 16$), and rectangular 64-QAM ($M = 64$) is given by [13]

$$P_M = 4\left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\frac{3\gamma}{M-1}\right) \cdot \left(1 - \left(1 - \frac{1}{\sqrt{M}}\right) Q\left(\frac{3\gamma}{M-1}\right)\right) \tag{3}$$

where the Q-function is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt$$

and γ is the subcarrier signal-to-noise ratio. To obtain the probability of bit error from Eq. (3), use the approximation $P_b \approx P_M / \log_2(M)$.

Using an incremental bit allocation algorithm, the signal constellation configuration for the subcarriers given $\text{BER}_{\text{Thres}}$ can be determined via the following algorithm:

1. Initialize the algorithm by setting the modulation scheme of all the subcarriers to 64-QAM and the subcarrier power levels to P_{1-MHz}/3 ~~$P_{1\text{-MHz}}/4$~~, where $P_{1\text{-MHz}}$ is the subband power constraint over any 1 MHz bandwidth in the U-NII band [14].
2. Determine the probability of bit error for all the subcarriers given the instantaneous subcarrier SNR values by using the closed form expressions for the probability of bit error.
3. If the mean BER, BER_{Mean}, is less than $\text{BER}_{\text{Thres}}$, the current configuration is kept and the algorithm is terminated. Otherwise, we proceed to Step 4.
4. Search for the subcarrier with the worst BER and check to see if it is BPSK-modulated. If it is, null the subcarrier and proceed to Step 5. Otherwise, reduce its constellation size, flag the subcarrier, and proceed to Step 6.
5. Readjust the power levels of the subcarrier adjacent to the recently nulled subcarrier, ensuring that the new power levels satisfy the 1 MHz bandwidth power constraint, and flag the subcarriers (see Section III-C for details).
6. Recompute the subcarrier BER values of all flagged subcarriers and return to Step 3.

In the next subsection, the power allocation algorithm that operates in tandem with the bit allocation algorithm is described.

C. Proposed Power Allocation Algorithm

Unlike the total power constraint used by most allocation algorithms [3–7, 9], a strict subband power constraint (such as the regulatory requirements of the FCC [14]) is employed in this work to reduce interference with other users. In applications such as wireless local area networks, the frequency bands of operation are usually unlicensed and users are non-cooperative. For these, power constraints are essential.

The subcarrier power allocation scheme operates by allocating to the non-nulled subcarrier i a power level of

$$P_i = P_{1\text{-MHz}} - \sum_{\substack{k=l \\ k \neq i}}^{\overset{l+2}{\cancel{l+3}}} P_k \tag{4}$$

where $P_{1\text{-MHz}}$ is the subband power constraint over any 1 MHz bandwidth. For the 5.15–5.25 GHz U-NII lower band [14], $P_{1\text{-MHz}}$ is equal to 2.5 mW. For instance, since four consecutive subcarriers constitute 1 MHz in IEEE 802.11a, to determine l use

$$l = \underset{\overset{(i-2)<=l<=i}{\cancel{(i-3)\leq l \leq i}}}{\arg\max} \left\{ \sum_{k=l}^{\overset{l+2}{\cancel{l+3}}} P_k \right\} \tag{5}$$

where the maximum power is constrained to be $P_{1\text{-MHz}}$. If all of the subcarriers are being used, each one has a transmit power level equal to ~~$P_{1\text{-MHz}}/4$~~. P_{1-MHz}/3

IV. Equalizer Tap Allocation

In Section II, we observed how the received composite signal was separated into N subcarriers. In OFDM systems, this is accomplished by using a serial-to-parallel converter. A cyclic prefix remover is then applied, followed by an FFT to demodulate the subcarrier signals. Although the distortion caused by the intersymbol interference (ISI) was mostly compensated for by the cyclic prefix, the received signal still suffers from the effects of interchannel interference (ICI) and noise. Therefore, as shown in Fig. 1, a set of subcarrier equalizers, $w^{(i)}(n)$, $i = 1, \ldots, N$, are employed to compensate for the remaining distortion.

Most multicarrier systems employ single-tap subcarrier equalizers to compensate for the distortion caused by the channel. These equalizers work well since the number of subcarriers is large enough such that the passband region of each subband is essentially flat. In this work, we drop this constraint on the number of subcarriers and propose an algorithm which employs multiple-tap subcarrier equalizers, where the number of taps per subcarrier is a function of the channel conditions.

A. Optimal MMSE Equalizer Design

Assuming the data across each subcarrier is transmitted in finite blocks length, we define an input block of length L transmitted across the k^{th} subcarrier as

$$\mathbf{x}^{(k)}_{n-L+1,n} = \left[x^{(k)}(n) \quad \cdots \quad x^{(k)}(n-L+1)\right]^T \tag{6}$$

where $\mathbf{x}^T$ is the transpose of $\mathbf{x}$.

Using the same technique employed in [11] and neglecting the cyclic prefix for now, we treat the FFT and IFFT blocks as Discrete Fourier Transform (DFT) and inverse DFT (IDFT) filterbanks, respectively. Therefore, the signal $\mathbf{x}^{(k)}_{n-L+1,n}$ is upsampled by N, filtered by the k^{th} synthesis filter $\mathbf{g}^{(k)}_{n-P+1,n}$, a channel impulse response $\mathbf{h}_{n-S+1,n}$, and the k^{th} analysis filter $\mathbf{f}^{(k)}_{n-P+1,n}$, before being downsampled by N and equalized by $\mathbf{w}^{(k)}_{n-Q+1,n}$.

Filtering is performed in this analysis by using convolution matrices. Therefore, we can represent $\mathbf{g}^{(k)}_{n-P+1,n}$ as an $(NQ+P+S-2) \times (NQ+2P+S-3)$ convolution matrix

$$\mathbf{G}^{(k)} = \begin{bmatrix} \mathbf{g}^{(k)\,T}_{n-P+1,n} & 0 & \cdots & 0 \\ 0 & \mathbf{g}^{(k)\,T}_{n-P+1,n} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{g}^{(k)\,T}_{n-P+1,n} \end{bmatrix} \tag{7}$$

Furthermore, the channel $\mathbf{h}_{n-S+1,n}$ and the k^{th} analysis filter $\mathbf{f}^{(k)}_{n-P+1,n}$, can be represented as $(NQ+P-1) \times (NQ+P+S-2)$ and $(NQ) \times (NQ+P-1)$ convolution matrices, $\mathbf{H}$ and $\mathbf{F}^{(k)}$, respectively. Finally, the upsampling and downsampling is performed using $(NQ+2P+S-3) \times L$ and $Q \times (NQ)$ matrices $\mathbf{T}_u$ and $\mathbf{T}_d$. Note that in order for the dimensions of the matrices and vectors to agree, L must be equal to

$$L = \left\lfloor \frac{NQ+2P+S-3}{N} \right\rfloor. \tag{8}$$

It has been shown in [11] that the cost function for a multicarrier modulation transmission system (excluding the addition and removal of a cyclic prefix), is given as

$$\begin{aligned} J^{(k)} &= \sigma^2_{x,k} + \mathbf{w}^{(k)\,H}_{n-Q+1,n}\mathbf{R}_x\mathbf{w}^{(k)}_{n-Q+1,n} \\ &\quad - \mathbf{w}^{(k)\,H}_{n-Q+1,n}\mathbf{p}_x - \mathbf{p}_x^H\mathbf{w}^{(k)}_{n-Q+1,n} \\ &\quad + \mathbf{w}^{(k)\,H}_{n-Q+1,n}\mathbf{R}_v\mathbf{w}^{(k)}_{n-Q+1,n}, \end{aligned} \tag{9}$$

while the optimal minimum mean-squared error (MMSE) equalizer was determined to be equal to

$$\mathbf{w}^{(k)}_{n-Q+1,n} = (\mathbf{R}_x + \mathbf{R}_v)^{-1}\,\mathbf{p}_x, \tag{10}$$

where

$$\mathbf{R}_x = \mathbf{T}_d\mathbf{F}^{(k)}\mathbf{H}\left(\sum_{l=1}^{N}\sigma_{x,l}^2\mathbf{G}^{(l)}\mathbf{T}_u\mathbf{T}_u^H\mathbf{G}^{(l)\,H}\right)\cdot\mathbf{H}^H\mathbf{F}^{(k)\,H}\mathbf{T}_d^H,$$
$$\mathbf{R}_v = \sigma_v^2\mathbf{T}_d\mathbf{F}^{(k)}\mathbf{F}^{(k)\,H}\mathbf{T}_d^H,$$
$$\mathbf{p}_x = \sigma_{x,k}^2\mathbf{T}_d\mathbf{F}^{(k)}\mathbf{H}\mathbf{G}^{(k)}\mathbf{T}_u\left[1 \quad \mathbf{0}_{1\times(L-1)}\right]^T,$$

and $\sigma_{x,k}^2$ and σ_v^2 are the signal variance of subcarrier k and the noise variance, respectively.

To include a cyclic prefix in the above derivation, a copy of the last T samples for a given OFDM symbol needs to be placed at the beginning of each OFDM symbol. If T is sufficiently long (longer than the channel impulse response), the dispersive effect of the channel is captured in the cyclic prefix, and discarded at the receiver.

To implement the cyclic prefix into the framework of this derivation, we define the $(NQ + P + S + T - 2) \times (NQ + P + S - 2)$ cyclic prefix insert matrix $\mathbf{C}_{(+)}$ in Eq. (11), and the $(NQ + P - 1) \times (NQ + P + T - 1)$ cyclic prefix remove matrix $\mathbf{C}_{(-)}$ in Eq. (12).

With these definitions the cost function and optimal MMSE equalizer would be the same as Eqs. (9) and (10), respectively, except that the correlation matrices and vector ($\mathbf{R}_x$, $\mathbf{R}_v$, and $\mathbf{p}_x$) transform into

$$\mathbf{R}_x = \mathbf{T}_d\mathbf{F}^{(k)}\mathbf{C}_{(-)}\mathbf{H}\mathbf{C}_{(+)}\cdot\left(\sum_{l=1}^{N}\sigma_{x,l}^2\mathbf{G}^{(l)}\mathbf{T}_u\mathbf{T}_u^H\mathbf{G}^{(l)\,H}\right)\cdot\mathbf{C}_{(+)}^H\mathbf{H}^H\mathbf{C}_{(-)}^H\mathbf{F}^{(k)\,H}\mathbf{T}_d^H,$$
$$\mathbf{R}_v = \sigma_v^2\mathbf{T}_d\mathbf{F}^{(k)}\mathbf{C}_{(-)}\mathbf{C}_{(-)}^H\mathbf{F}^{(k)\,H}\mathbf{T}_d^H,$$
$$\mathbf{p}_x = \sigma_{x,k}^2\mathbf{T}_d\mathbf{F}^{(k)}\mathbf{C}_{(-)}\mathbf{H}\mathbf{C}_{(+)}\mathbf{G}^{(k)}\mathbf{T}_u\cdot\left[1 \quad \mathbf{0}_{1\times(L-1)}\right]^T.$$

Now that an expression for the distortion has been derived, we can use it in the adaptive algorithms in the next section.

B. Proposed Equalizer Tap Allocation Algorithm

The tap allocation algorithm is based on the previous work by authors in [11]. Having perfect channel knowledge, the algorithm operates per subcarrier as follows:

1. Set the number of taps for subcarrier i, $Q^{(i)}$, to 1.
2. Solve for the optimal set of equalizer taps, $w^{(i)}(n)$, and compute the cost function of Eq. (9), $J^{(i)}$.
3. If $J^{(i)}$ is below the pre-established threshold for the MSE, keep $w^{(i)}(n)$ as the final equalizer tap values for subcarrier i and terminate the algorithm, otherwise proceed to Step 4.
4. If the difference between the current and previous MSE values is less than a specified percentage, terminate the algorithm and keep $w^{(i)}(n)$, otherwise increase the number of taps by $Q^{(i)} = Q^{(i)} + 1$ and proceed to Step 2.

for all subcarriers $i = 1, \ldots, N$.

V. Results

A. Simulation Setup

The results for the proposed bit allocation and bit/power/tap allocation algorithms are presented. It should be noted that the SNR is defined here as the nominal transmitted power divided by the noise power in the signal bandwidth. When measured this way, the SNR values tend to be large due to the channel attenuation. Furthermore, the signal constellations used in this work are BPSK, QPSK, rectangular 16-QAM, and rectangular 64-QAM. The subcarrier can also be nulled, depending on channel conditions. Finally, the statistical indoor propagation modelling technique devised by Saleh and Valenzuela [15] was used to generate the channel responses.

$$\mathbf{C}_{(+)} = \left[\begin{array}{c|c|c} \begin{array}{c} \mathbf{I}_{N\times N} \\ \hline \mathbf{I}_{T\times T} \;\; \mathbf{0}_{T\times N-T} \end{array} & \multicolumn{2}{c}{\mathbf{0}_{(N+T)\times(N(Q-1)+P+S-2)}} \\ \hline \mathbf{0}_{(N+T)\times N} & \begin{array}{c} \mathbf{I}_{N\times N} \\ \hline \mathbf{I}_{T\times T} \;\; \mathbf{0}_{T\times N-T} \end{array} & \mathbf{0}_{(N+T)\times(N(Q-2)+P+S-2)} \\ \hline \vdots & & \vdots \end{array}\right] \qquad (11)$$

$$\mathbf{C}_{(-)} = \left[\begin{array}{c|c|c} \mathbf{I}_{N\times N} \;\; \mathbf{0}_{N\times T} & \mathbf{0}_{N\times(N+T)} & \cdots \\ \hline \mathbf{0}_{(N(Q-1)+P+S-2)\times(N+T)} & \begin{array}{c} \mathbf{I}_{N\times N} \;\; \mathbf{0}_{N\times T} \\ \hline \mathbf{0}_{(N(Q-2)+P+S-2)\times(N+T)} \end{array} & \cdots \end{array}\right] \qquad (12)$$

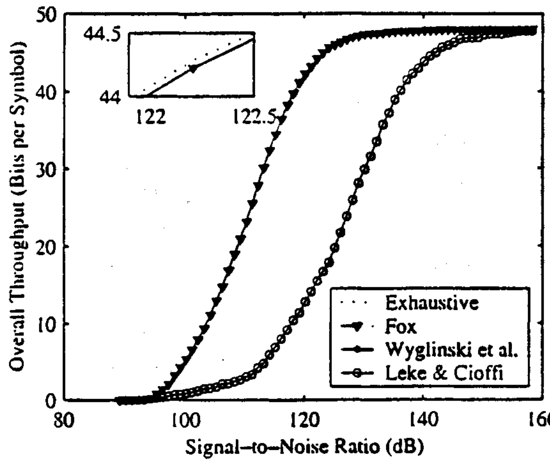


Fig. 2 Throughput of systems with 8 subcarriers satisfying a BER_{Thres} of 10^{-3}

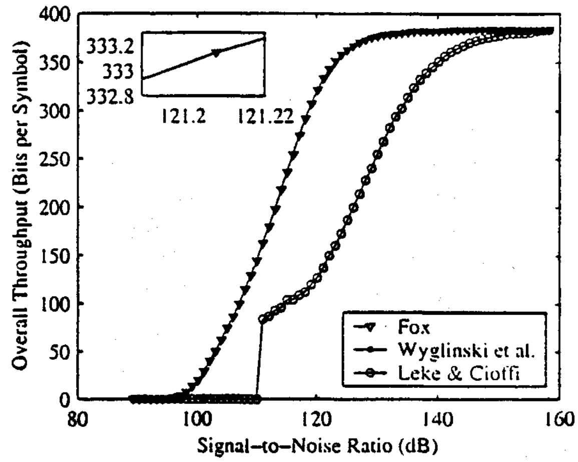


Fig. 4 Throughput of systems with 64 subcarriers satisfying a BER_{Thres} of 10^{-5}

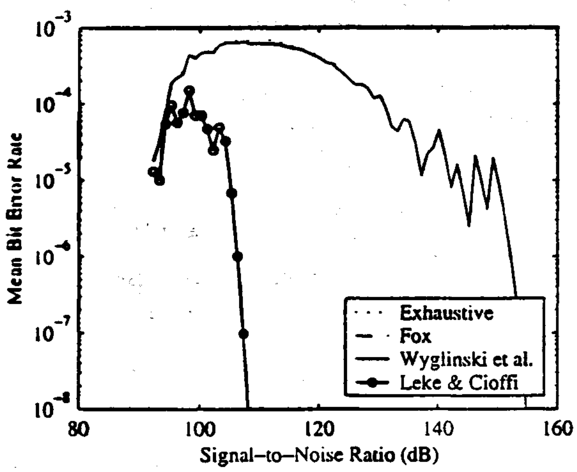


Fig. 3 Mean BER of systems with 8 subcarriers satisfying a BER_{Thres} of 10^{-3}

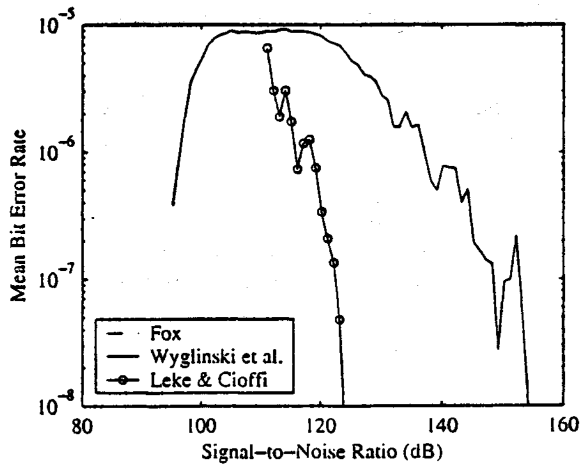


Fig. 5 Mean BER of systems with 64 subcarriers satisfying a BER_{Thres} of 10^{-5}

For the bit allocation results, the proposed system is compared with the bit allocation algorithms of Fox [16] and Leke & Cioffi [7] for system configurations of 8 and 64 subcarriers. Furthermore, an exhaustive search algorithm was also employed for the 8 subcarrier case in order to determine how close the various methods were to the optimal allocation. For each channel realization, the algorithms were operating at 70 different SNR values ranging from 88 dB to 156 dB. The trials were repeated for 50 different channel realizations and the results averaged.

The bit/power/tap allocation results with respect to the throughput, bit allocation, and tap allocation are presented for the adaptive OFDM and IEEE 802.11a compliant system. For a fair comparison, 52 subcarriers are employed in the system. A BER_{Thres} of 10^{-3} was used in these experiments and the simulations were ran until the BER values were within 10 percent of the mean.

B. Bit Allocation

In Fig. 2, the overall throughput of the four bit allocation algorithms are presented. It is readily observable that out of the four algorithms, the algorithm of Leke and Cioffi is performing substantially worse than the other algorithms. In fact, it does not reach the same throughput as the other systems until high SNR values of 150 dB. As for the other methods, the difference in throughput between them is minuscule but their order is significant. The largest throughput is produced by the exhaustive search algorithm, followed by both Fox's and the proposed algorithms. Since the objective function is not concave and the constraint

TABLE 1 NUMBER OF BER_{Thres} VIOLATIONS BY LEKE & CIOFFI, 8 SUBCARRIER SYSTEM, $BER_{Thres} = 10^{-3}$

SNR (dB)	90	92	97	102	110
Violations.	0%	2%	12%	6%	0%

TABLE 2 NUMBER OF BER_{Thres} VIOLATIONS BY LEKE & CIOFFI, 64 SUBCARRIER SYSTEM, $BER_{Thres} = 10^{-5}$

SNR (dB)	90	110	113	120	123
Violations.	100%	100%	88%	6%	0%

function is not strictly convex, there is no guarantee that Fox's algorithm would reach the optimal allocation [16].

The BER_{Mean} values corresponding to the throughputs in Fig. 2 are shown in Fig. 3. It can be observed that all the algorithms, except for Leke and Cioffi, have approximately the same values. The small differences between the three methods is due to how many more bits each algorithm can allocate while still satisfying BER_{Thres}. Since the exhaustive search algorithm has the largest throughput relative to the other algorithms, its values for BER_{Mean} is the largest. This is followed by the algorithms of both Fox and the proposed algorithm. As for the algorithm by Leke & Cioffi, its values BER_{Mean} are significantly lower than the other algorithms due to its low throughput. Since the algorithm of Leke and Cioffi does not check if the bit allocation exceeds BER_{Thres}, there is a possibility that BER_{Thres} may be violated. In such cases, the results of that allocation are not considered. Table 1 shows the number of violations as a percentage of the total number of channel realizations per SNR value.

The results are similar when 64 subcarriers are employed, as shown in Fig. 4. In this case, the exhaustive search algorithm was omitted for simplicity. The remaining algorithms, except for Leke and Cioffi, achieve nearly the same throughput with some small differences. The throughput of the algorithm of Leke and Cioffi is substantially less than that of the other methods, only reaching the other algorithms at high SNR values. Note how at low SNR values, the algorithm of Leke and Cioffi goes to zero. This is due to the algorithm producing all its allocations that exceed BER_{Thres}. Table 2 shows the number of violations.

The corresponding BER_{Mean} values are shown in Fig. 5. They show that all the algorithms, except for Leke and Cioffi, have approximately the same values. As for the algorithm of Leke and Cioffi, its values for BER_{Mean} are lower due to its low throughput while some of its values go down to zero at low SNR because of BER_{Thres} violations, as shown in Table 2.

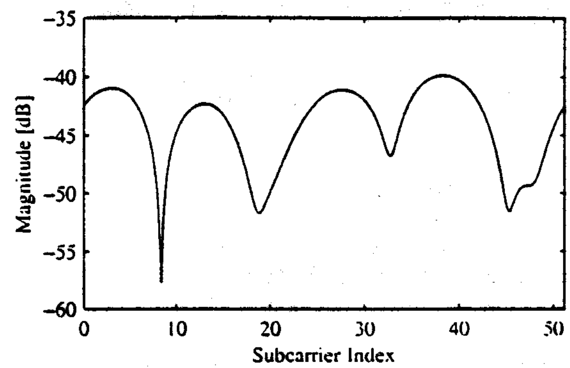


Fig. 6 Frequency response of an indoor channel environment in the 5.15–5.25 GHz U-NII band with transmitter/receiver distance of 50 m

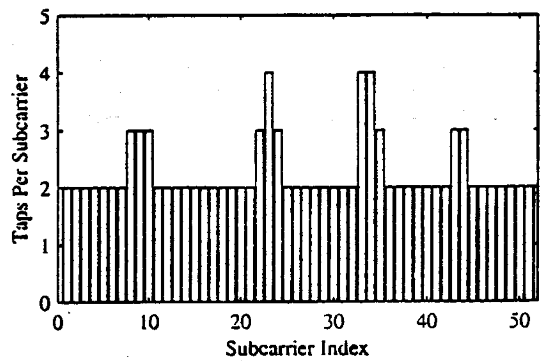


Fig. 7 Subcarrier equalizer tap allocation for a 52 subcarrier system at ~~130~~ 99 dB satisfying a BER_{Thres} of 10^{-3}

As seen in Figs. 2 and 4, the throughput of the proposed algorithm is very close to that of the optimal algorithm. However, as for the execution times, the proposed algorithm executes much more quickly relative to either Fox or Leke and Cioffi for SNR values of 110 dB or greater. A summary of several execution times for the 64 subcarrier case with a BER_{Thres} of 10^{-3} are shown in Table 3. All algorithms were programmed in C and executed on an Intel Pentium IV 2 GHz computer.

TABLE 3 MEAN EXECUTION TIMES (IN MILLISECONDS) AT DIFFERENT SNR VALUES, 64 SUBCARRIERS, $BER_{Thres} = 10^{-3}$

Algorithm	90 dB	97 dB	114 dB	131 dB
Fox	1.02	1.38	1.85	2.05
Wyglinski	1.58	1.52	1.31	1.10
Leke	1.20	1.16	1.30	1.25

C. Bit/Power/Tap Allocation

Referring to Fig. 8, it is observed that the throughput performance of the systems overlap when the SNR is 112 dB or more. If the basic IEEE 802.11a system does not achieve the BER threshold, the throughput of the system is zero. The main advantage of the adaptive systems is the ability to transmit data given a BER constraint while accepting a penalty in throughput. Moreover, we see that the throughput of adaptive multicarrier systems improves for low SNR values when subcarrier power reallocation is employed. None of the non-power reallocating systems are transmitting when the SNR is below 80 dB. The power reallocating systems continue to transmit, although at relatively low throughput.

In Fig. 9, it is observed that as the SNR increases, the subcarrier performance improves uniformly and the signal constellation size increases. Ultimately, when the SNR is high, say 112 dB or greater, all available subcarriers are modulated with 64-QAM.

In Fig. 10, it is observed that when the SNR is low, very few subcarriers are used, therefore there are not many places where taps can be allocated in the first place. As the SNR increases, there are fewer nulled subcarriers so more taps can be assigned. As the noise power decreases even further, the system needs only a few taps to achieve adequate performance.

The allocation of equalizer taps across 52 subcarriers for an SNR value of ~~130~~ 99 dB when BER_{Thres} is 10^{-3} is shown in Fig. 7. Both the adaptive and IEEE 802.11a-compliant systems employ cyclic prefixes that are 12 taps in length. Comparing the allocation with the corresponding channel frequency response in Fig. 6, which has a length of 20 taps, several observations can be made. When the channel response is relatively flat, the number of taps allocated is small. On the other hand, the subcarriers affected by deep nulls and steep portions of the channel have a large number of taps allocated to them. As a result, it is obvious that the required number of equalizer taps per subcarrier is different across all the subcarriers, thus the amount of redundant taps allocated is minimized. Furthermore, the cyclic prefix is not sufficiently long enough to remove the ISI, thus multi-tap equalizers per subcarrier are required to compensate for the remaining channel distortion.

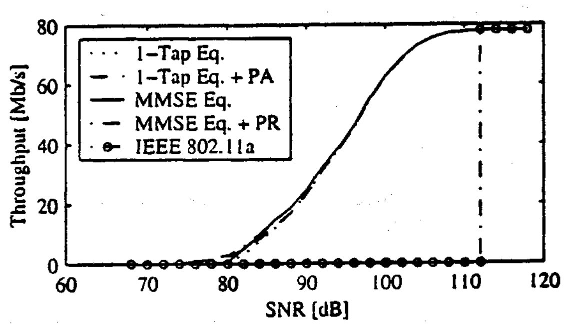


Fig. 8 Throughput of the adaptive OFDM system (1-tap or MMSE equalizer, with or without power allocation (PA)) and the IEEE 802.11a-compliant system

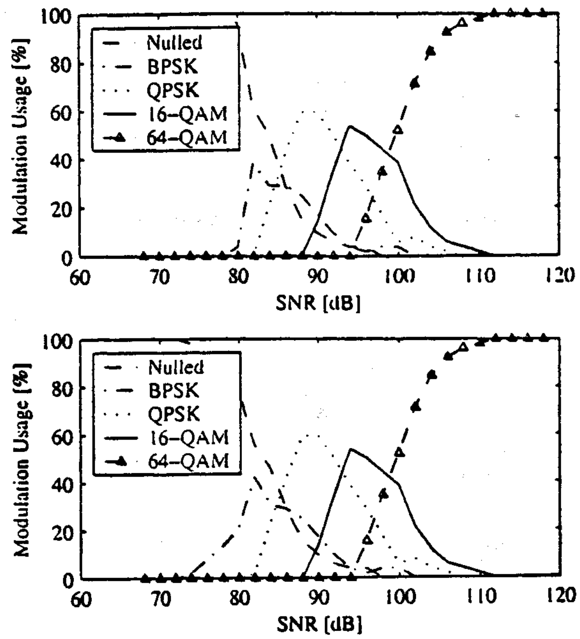


Fig. 9 Bit allocation of the adaptive OFDM system employing either power reallocation (bottom) or no power reallocation (top)

VI. Conclusion

In this paper a new adaptive bit and power allocation algorithm for multicarrier systems was presented which enhanced system throughput while satisfying mean bit error rate and subband power constraints. Results showed that the proposed bit allocation algorithm approaches the optimal solution while its complexity is lower than other algorithms. The proposed power allocation algorithm exhibits improved system performance at low SNR values, while satisfying regulatory requirements. Finally, the equalizer tap allocation eliminates the possibility of redundant tap allocations by assigned taps according to channel conditions.

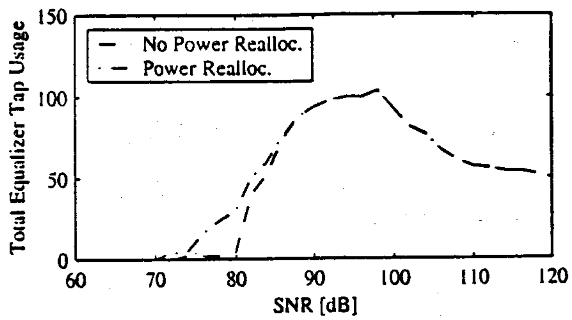


Fig. 10 Tap allocation of the adaptive OFDM system with and without power reallocation

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