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A Novel Power Distribution Scheme Combined with Adaptive Modulation Based on Subcarrier Grouping for OFDM Systems*

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SUMMARY In this paper, we propose to adapt both the modulation scheme and the transmit power in the frequency domain using a heuristic evaluation of the bit error rate (BER) for each subcarrier. The proposed method consists in ordering in terms of fading impact, grouping a certain number of subcarriers and performing local power adaptation in each subcarrier group. The subcarrier grouping is performed in order to equalize the average channel condition of each subcarrier group. Grouping and local power adaptation allow us to take advantage of the channel variations and to reduce the computational complexity of the proposed power distribution scheme, while avoiding the performance degradation due to the suboptimum power adaptation as much as possible. Compared to the conventional power distribution methods, the proposed scheme does not require any iterative process and the power adaptation is directly performed using an analytical formula. Simulations show a gain in terms of BER performance compared to equal power distribution and existing algorithms for power distribution. In addition, due to the subcarrier group specificity, the trade-off between the computational complexity and the performance can be controlled by adjusting the size of the subcarrier groups. Simulation results show significant improvement of BER performance compared to equal power allocation.
key words: *OFDM, adaptive modulation, Lagrangian method, global BER optimization*

1. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) [1] has recently been applied widely in wireless communication systems due to its high data rate transmission capability with high bandwidth efficiency. Since the channel matrix becomes a circulant matrix because a cyclic prefix (CP) is used and the circulant matrix can be diagonalized by discrete Fourier transform (DFT) matrix, OFDM transmission can achieve independent parallel flat fading channels. This means that the transmission performance can be improved by adequately (and inequally) distributing the total transmission power among the subcarriers. Assuming that the channel state information (CSI) for all the subcarriers is available at the transmitting part, several power and bit allocation schemes have been proposed [2]-[4], whose optimization criterion is the minimization of the total transmitted power for fixed bit error rate (BER). In [2], Z. Song et al. proposed a statistical adaptive modulation for quadrature amplitude modulation (QAM)-OFDM systems. The modulation selection is performed by an iterative process so as to minimize the BER, which implies high computational and system complexity. The Chow's algorithm [3] uses a criterion of minimizing the packet error rate while attaining a certain transmission rate, which also requires a complex iterative process. [4] proposes two different block adaptive modulation techniques, which allocate the same modulation level for adjacent subcarriers following an iterative Greedy process [5]. However, joint power allocation is not included in [4] and the adjacent criteria to allocate similar modulation is affected both by the channel variations and also the system parameters. On the other hand, maximizing the spectral efficiency is another way to optimize the transmission performance [6]-[8]. In [6], the water-filling method is used to allocate power in order to maximize the system capacity. In [7], a multilevel transmit power scheme is proposed for OFDM with adaptive modulation. And in [8], a method to improve the modulation selection including the long-term power prediction scheme is proposed. The data rate and the transmit power are both adapted to maximize the spectral efficiency. However, in the methods presented in [6]-[8], the adaptative modulation and/or the power allocation are performed among all the subcarriers by an iterative process. Finally, in [9], a suboptimal scheme to improve the BER is proposed and performances in a multicarrier system with diversity are presented. However, impact of the channel variation (ordering the subcarriers in term of fading impact) and effect of the complexity are not considered.

In this paper, we propose to first group and order the different subcarriers which compose the OFDM symbol considering their fading impacts and then adapt both the modulation scheme and the transmit power in the frequency domain using a heuristic expression of the BER [10]-[11] for each subcarrier. Simplicity of the

Manuscript received September 13, 2007.
Manuscript revised July 22, 2008.
Final manuscript received November 07, 2006.
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*This paper has been partially presented at the PIMRC conference, Helsinki, Finland, September 11-14, 2006.

BER expression allows us to obtain a closed form expression of the optimum power to be allocated for each subcarrier, which is applicable not only for uncoded OFDM systems but also for coded ones. Although the local power adaptation using a subset of the subcarriers results in poor performance in general, we propose a subcarrier grouping method that minimizes the adverse impact of the local power adaptation by taking the channel gains of all the subcarriers into consideration. The grouping and the power allocation also allow us to control the balance between the transmission performance and the computational complexity by adjusting the size of the subcarrier group. Simulation results show significant improvements of BER performance both in the uncoded and coded cases compared to the scheme proposed in [9].

The rest of the paper is organized as follows. In Section 2, we describe the signal model of the proposed scheme. In Section 3, we firstly introduce the BER approximation and then describe the proposed modulation and power adaptation scheme in the frequency domain. In Section 4, numerical results over QPSK and QAM modulations with several coding gains are presented. Finally, conclusions are drawn in Section 5.

2. Signal Modeling

We consider the OFDM system that transmits N modulated data symbols in an OFDM symbol period through N subcarriers. For the i-th OFDM symbol, the n-th sample of the OFDM signal is expressed as [12]:

$$s_{i,n} = \frac{1}{\sqrt{N}} \cdot \sum_{k=0}^{N-1} \sqrt{p_k} \cdot x_{i,k} \cdot \exp\left\{ j\frac{2\pi nk}{N} \right\}, \quad (1)$$

where $x_{i,k}$ is the modulated data symbol of the i-th OFDM symbol on the k-th subcarrier and p_k is the allocated power of the k-th subcarrier. To combat inter-symbol interference (ISI) and inter-carrier interference (ICI), a guard interval (GI) [13], such as the CP or the zero padding (ZP), is added to each OFDM symbol. In the case of the CP, the last N_g samples of every OFDM symbol are copied and added to the heading part. The transmitted signal can be expressed as

$$\tilde{s}_{i,n} = \begin{cases} s_{i,N-N_g+n} & \text{for } 0 \leq n < N_g \\ s_{i,n-N_g} & \text{for } N_g \leq n < N + N_g \end{cases}. \quad (2)$$

We suppose that the fading channel can be modeled by a finite impulse response (FIR) filter. When the maximum delay spread does not exceed the GI, in the discrete frequency domain, the j-th received OFDM symbol for m-th sub-carrier is given by

$$y_{j,m} = h_m \cdot \sqrt{p_m} \cdot x_{j,m} + n_{j,m}, \quad (3)$$

where h_m is a channel coefficient for the m-th subcarrier and $n_{j,m}$ denotes a zero mean additive white Gaussian noise (AWGN) of variance σ_n^2. Thus it results in a frequency-flat-fading signal model per sub-carrier. Channel correction is simply achieved by multiplying on each subcarrier the inverse of the channel coefficient in the zero forcing (ZF) linear detector. The channel equalizer can be expressed as

$$G_m = \frac{h_m^*}{|h_m|^2}. \quad (4)$$

3. Proposed Power Allocation Scheme

The proposed scheme is based on a simple procedure which consists of performing frequency domain optimization of the transmit power in terms of the CSI and the expression of the approximated BER [14]. Adaptive modulation can be integrated into the proposed scheme as an additional constraint of the optimization problem.

3.1 Bit Error Rate Approximation

Recently, it has been proposed in [15] and [16] that a heuristic expression to approximate the BER is expressed as

$$f(M_m, p_m) \approx a_m \cdot \exp\left\{ -\frac{b_m}{M_m} \cdot \beta_m \cdot p_m \right\} \quad (5)$$

where β_m is equal to:

$$\beta_m = \frac{1}{\sigma_n^2 \cdot |G_m|^2} \quad (6)$$

and:

$$M_m = 2^{B_m} - 1 \quad (7)$$

where B_m is the number of bits per symbol ($B_m = 2$ for QPSK, $B_m = 4$ for 16-QAM and $B_m = 6$ for 64-QAM) and β_m denotes a signal-to-noise ratio (SNR) on the m-th subcarrier, which depends on the modulation scheme and the equalizer weights. In addition, the impact of the modulation in the expression of the BER is included with the parameter M_m. The selection of the modulation level is developed in Section 3.3. Parameters a_m and b_m are to be determined in a heuristic way, i.e., via computer simulations. In this paper, we consider the following two OFDM systems [16]:

- -Uncoded OFDM: Without forward error correction (FEC) and with QPSK or QAM modulations.
- -Convolutionally coded OFDM: With the convolutional code in [17] and [18]. The generator polynomial of the mother code is $g = [133, 171]$. The coding rates are controlled by the puncturing pattern specified in [17].

Tables 1, 2 and 3 respectively summarize the parameters of a_m and b_m for QPSK, 16-QAM and 64-QAM

Table 1 Parameters of a_m and b_m: QPSK modulation

Coding Rate	1/2	3/4	1
Rate (bits/symb.)	1	1.5	2
a_m	7	16	0.2
b_m	9.5	5.4	1.66

Table 2 Parameters of a_m and b_m: 16-QAM modulation

Coding Rate	1/2	3/4	1
Rate (bits/symb.)	2	3	4
a_m	4	14	0.2
b_m	11	6	1.73

Table 3 Parameters of a_m and b_m: 64-QAM modulation

Coding Rate	1/2	3/4	1
Rate (bits/symb.)	3	4.5	6
a_m	1.5	7	0.15
b_m	12	6	1.68

obtained via computer simulations. In the tables, the coding rate of 1 means the uncoded OFDM system. In addition, the coding unit is the transmit frame, which is composed of several OFDM symbols. The total transmit duration is within the coherent time. In the next section, we will detail the validity of the unit coding for the proposed power allocation and will illustrate it with performance simulations.

In the rest of the paper, we will use the BER expression described in (5) as an approximated expression to perform power allocation and group selection.

3.2 Subcarrier Group Selection

Fig. 1 illustrates the principle of forming subcarrier groups of size N_s. If transmission performance is to be maximized as the first criterion, power allocation through whole subcarriers is the best. However, the computational complexity of the power allocation increases faster than linearly as the number of subcarriers to be considered increases, in general. Hence, the computational complexity can be reduced by performing power distribution for a limited number of subcarriers (N_s) at a time and repeating it N/N_s times. This approach is suboptimal and suffers from performance degradation, while how much the performance degrades depends on how the subcarrier groups are formed.

Let $\boldsymbol{\beta}$ denotes a vector representation of β_m in (5) as $\boldsymbol{\beta} = [\beta_0 \cdots \beta_{N-1}]^T$. We firstly find an $N \times N$ permutation matrix $\mathbf{F}$, which results in the arrangement of the elements of $\boldsymbol{\beta}$ in the descending order as

$$\boldsymbol{\gamma} = \mathbf{F} \cdot \boldsymbol{\beta}, \tag{8}$$

where $\boldsymbol{\gamma} = [\gamma_0 \cdots \gamma_{N-1}]^T$ and $\gamma_0 > \gamma_1 > ... > \gamma_{N-1}$.

In order to keep the average channel condition of each subcarrier group to be the same for all the subcarrier groups, we rearrange the subcarriers by folding the last half of the element of $\boldsymbol{\gamma}$ to the first as

$$\boldsymbol{\alpha} = \mathbf{D} \cdot \boldsymbol{\gamma}, \tag{9}$$

where $\boldsymbol{\alpha} = [\alpha_0 \cdots \alpha_{N-1}]^T$ and $\mathbf{D}$ is also an $N \times N$ permutation matrix defined as

$$\mathbf{D} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 0 & 1 \\ 0 & 1 & 0 & \cdots & 0 & 0 & 0 \\ 0 & 0 & 0 & \cdots & 0 & 1 & 0 \\ & & & \cdots & & & \end{bmatrix}. \tag{10}$$

Using $\boldsymbol{\alpha}$, we finally obtain the subcarrier groups as

$$\boldsymbol{\alpha}^{(t)} = \left[\alpha_{t \cdot N_s} \quad \cdots \quad \alpha_{t \cdot N_s + N_s - 1}\right]^T, \tag{11}$$

where $\boldsymbol{\alpha}^{(t)}$ is the t-th group of the equivalent SNR, ($t = 0, ..., N/N_s - 1$). Therefore, defining $\mathbf{p} = [p_0 \cdots p_{N-1}]^T$, the transmitted power vector of the t-th subcarrier group $\mathbf{p}^{'(t)}$ can therefore be obtained as

$$\mathbf{p}^{'} = \left[\mathbf{p}^{'(0)T} \quad \cdots \quad \mathbf{p}^{'(N/N_s-1)T}\right]^T = \mathbf{D} \cdot \mathbf{F} \cdot \mathbf{p}, \tag{12}$$

where $\mathbf{p}^{'(t)} = [p^{'}_{t \cdot N_s} \cdots p^{'}_{t \cdot N_s + N_s - 1}]^T$.

In the proposed scheme, power allocation is performed for each $\mathbf{p}^{'(t)}$ and is repeated N/N_s times. Denoting the optimum vectors of $\mathbf{p}^{'(t)}$ and $\mathbf{p}^{'}$ as $\mathbf{p}_o^{'(t)} = [p^{'}_{t \cdot N_s, o} \cdots p^{'}_{t \cdot N_s + N_s - 1, o}]^T$, and $\mathbf{p}^{'}_o$, respectively, we can express the optimum transmitted power vector $\mathbf{p}_o = [p_{0,o} \cdots p_{N-1,o}]^T$ as

$$\mathbf{p}_o = \mathbf{F}^{-1} \cdot \mathbf{D}^{-1} \cdot \mathbf{p}^{'}_o. \tag{13}$$

Similarly, we define a modulation level vector and a modulation level vector for the t-th subcarrier as $\mathbf{B} = [B_0 \cdots B_{N-1}]^T$ and $\mathbf{B}^{'(t)} = [B^{'}_{t \cdot N_s} \cdots B^{'}_{t \cdot N_s + N_s - 1}]^T$, respectively. Also, we denote optimum vectors of $\mathbf{B}$ and $\mathbf{B}^{'(t)}$ as $\mathbf{B}_o = [B_{0,o} \cdots B_{N-1,o}]^T$ and $\mathbf{B}_o^{'(t)} = [B^{'}_{t \cdot N_s, o} \cdots B^{'}_{t \cdot N_s + N_s - 1, o}]^T$, respectively. $\mathbf{B}_o$ is expressed as

$$\mathbf{B}_o = \mathbf{F}^{-1} \cdot \mathbf{D}^{-1} \cdot \mathbf{B}^{'}_o. \tag{14}$$

where $\mathbf{B}^{'}_o = [\mathbf{B}_o^{'(0)T} \cdots \mathbf{B}_o^{'(N/N_s-1)T}]^T$.

3.3 Proposed Power Allocation Combined with Adaptive Modulation

In this section, we consider power distribution combined with adaptive modulation for the t-th subcarrier group under the condition that the average transmit power and the average modulation level are kept constant to be $\overline{P}$ and $\overline{B}$, respectively. The optimization problem can be given by

$$\begin{cases} (\mathbf{p}_o^{'(t)}, \mathbf{B}_o^{'(t)}) = \arg \min\limits_{\mathbf{p}^{'(t)}, \mathbf{B}^{'(t)}} \sum\limits_{k=0}^{N_s-1} \frac{f(M^{'}_{t \cdot N_s + k}, p^{'}_{t \cdot N_s + k})}{N_s} \\ \text{s.t.} \sum\limits_{m=0}^{N_s-1} B^{'}_{t \cdot N_s + m} = N_s \cdot \overline{B} \\ \text{s.t.} \sum\limits_{m=0}^{N_s-1} p^{'}_{t \cdot N_s + m} = N_s \cdot \overline{P} \end{cases} \tag{15}$$

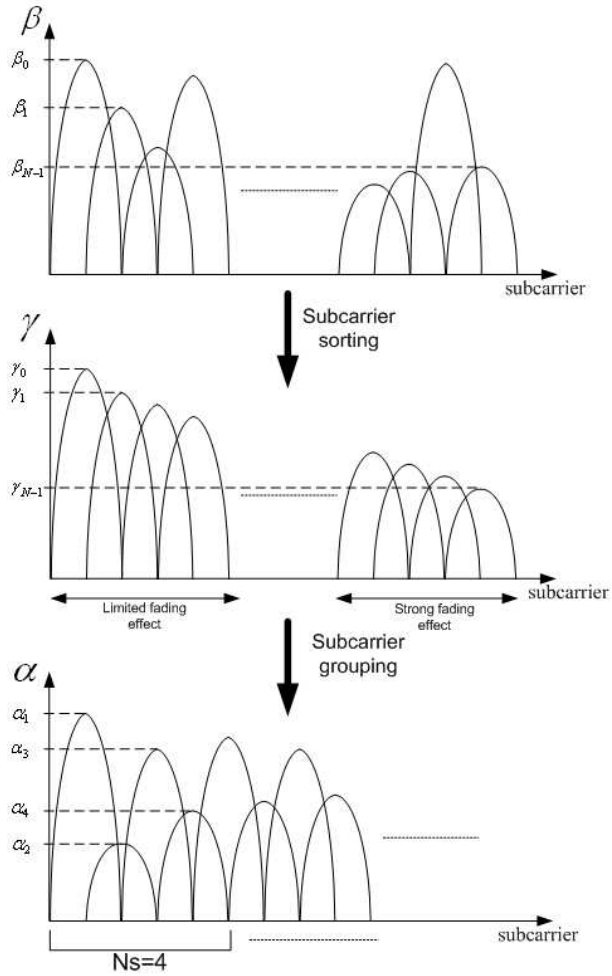

Fig. 1 Principle of subcarrier group selection

where $M'_{t\cdot N_s+k} = 2^{B'_{t\cdot N_s+k}} - 1$. To solve the problem, we have firstly obtained a closed form solution of the power distribution in terms of modulation levels by solving

$$\begin{cases} \mathbf{p}_o^{\prime(t)} = \arg\min_{\mathbf{p}^{\prime(t)}} \sum_{m=0}^{N_s-1} \frac{f(M'_{t\cdot N_s+m}, p'_{t\cdot N_s+m})}{N_s} \\ \text{s.t.} \ \sum_{m=0}^{N_s-1} p'_{t\cdot N_s+m} = N_s \cdot \overline{P} \end{cases} . \qquad (16)$$

Since this is a common minimization problem with a linear constraint, we can solve it by using the Lagrange multiplier method. The closed form optimum solution is expressed as

$$p'_{t\cdot N_s+m,o} = \left[\sum_{u=0}^{N_s-1} \frac{M'_{t\cdot N_s+u} \cdot \alpha_{t\cdot N_s+m} \cdot b_m}{M'_{t\cdot N_s+m} \cdot \alpha_{t\cdot N_s+u} \cdot b_u} \right]^{-1} \cdot \Bigg[N_s\overline{P} + \sum_{u=0}^{N_s-1} \frac{M'_{t\cdot N_s+m}}{\alpha_{t\cdot N_s+u} \cdot b_u} \log\left(\frac{M'_{t\cdot N_s+u} \cdot \alpha_{t\cdot N_s+m} \cdot a_m \cdot b_m}{M'_{t\cdot N_s+m} \cdot \alpha_{t\cdot N_s+u} \cdot a_u \cdot b_u} \right) \Bigg]. \qquad (17)$$

Since we have ignored the range of $p'_{t\cdot N_s+m}$ for the sake of simplicity, the solution may result in $p'_{t\cdot N_s+m,o} < 0$ for some cases. In this case, we propose to apply equal power distribution for the subcarrier group.

By substituting (16) into (15), we obtain an optimization problem for the adaptive modulation as

$$\begin{cases} \mathbf{B}_o^{\prime(t)} = \arg\min_{\mathbf{B}^{\prime(t)}} \sum_{m=0}^{N_s-1} \frac{f(M'_{t\cdot N_s+m}, p'_{t\cdot N_s+m,o})}{N_s} \\ \text{s.t.} \ \sum_{m=0}^{N_s-1} B'_{t\cdot N_s+m} = N_s \cdot \overline{B} \end{cases} . \qquad (18)$$

Unlike (16), it is difficult to obtain a closed form solution of (18). However, thanks to a lower number of subcarriers due to the proposed subcarrier group selection and the limited number of choices of modulation level in general, we can search modulation schemes exhaustively in order to obtain the solution of (18). More precisely, we firstly select all the possible modulation level vectors which satisfy the constraint on the average modulation level. For each modulation level vector, the optimum transmission power of each subcarrier is obtained by (17). Then, we compute the cost function in (18) for this modulation level vector, and finally, we select a vector which minimizes the average BER.

In the case of a fixed modulation ($B_m = B$ and $M = 2^B - 1$) and coding rate R, the parameters a_m and b_m are fixed, known and respectively equal to a and b for each subcarrier. Therefore, we can obtain the optimum transmission power from (17) without solving (18). For this fixed modulation case, we limit the optimization problem to the power distribution case and (17) can be simplified as

$$p'_{t\cdot N_s+m,o} = \left[\sum_{u=0}^{N_s-1} \frac{\alpha_{t\cdot N_s+m}}{\alpha_{t\cdot N_s+u}} \right]^{-1} \cdot \Bigg[N_s\overline{P} + \sum_{u=0}^{N_s-1} \frac{M}{\alpha_{t\cdot N_s+u} \cdot b} \log\left(\frac{\alpha_{t\cdot N_s+m}}{\alpha_{t\cdot N_s+u}} \right) \Bigg]. \qquad (19)$$

Moreover, contrary to the waterfilling scheme [6], the proposed scheme tends to allocate more power to the subcarrier that are strongly affected by channel fading. The proposed solution tends to flatten the channel variation, so that an uniform coding scheme between the different subcarrier is possible and appropriate.

3.4 Computational Complexity

The two main advantages of the proposed scheme are the simplicity compared to the iterative algorithms such as the steepest decent [9] and the low additional complexity [9] compared to the suboptimal solution which does not include any specific group selection based on the knowledge of the channel condition in the power allocation process. Complexity of the steepest descent algorithm is basically equal to $O(N_s^3)$. In addition, the

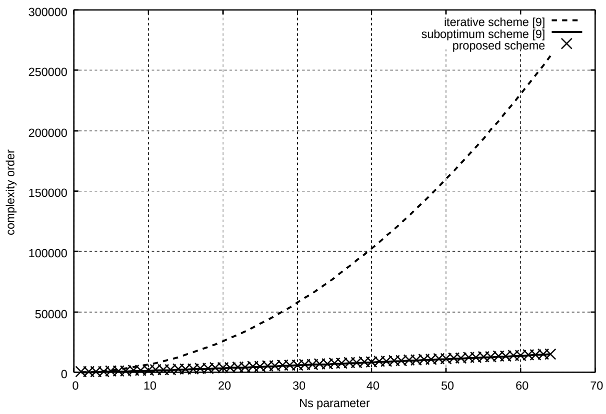

Fig. 2 Complexity evaluation for $N = 64$ and $0 < N_s < 64$

iterative process needs to be repeated N/N_s (for simplicity, we assume that N_s/N is an integer). The complexity of the ordering part of the suboptimum power allocation that we propose, is equal to $O(4 \cdot N \cdot Log(N))$ and is performed only twice for each OFDM frame. The analytical part of the calculation that is performed for the estimation of the power allocation is equal to $O(N_s^2 \cdot Log(N_s^2))$. Fig. 2 shows the computational complexity in term of subcarrier groups. Fig. 2 highlights that complexity of the proposed scheme is less complex than the iterative method. In addition, the obtained complexity is similar to that of the suboptimum proposal described in [9].

4. Numerical Experimentation

This section gives an evaluation of the performance of the proposed power allocation method for OFDM systems in a mutli-path fading environment. Simulation parameters are given in Table 4. We assume perfect knowledge of the CSI both at the transmitting and receiving parts. For all simulations, the delay power spectrum is assumed to be an exponential decay model with 1 dB decaying per sampling period. The carrier frequency is equal to 2.4GHz, the IFFT/FFT size is 64 points and the guard interval is set to 16 samples. The ZF detection scheme is employed in the receiver.

For comparison, two additional systems have been included in the simulations. For uncoded and fixed modulation, the optimal power allocation proposed by [9] is plotted. Based on the exact function of the BER for QPSK and QAM modulations, combined with a steepest descent algorithm, optimal power allocation is estimated and adapted. The second system is the sub-optimal case described in [9]. This suboptimum case consists of performing power allocation without any consideration for the channel variation in the subcarrier groups. In the rest of the paper, the optimum system will be represented by the plot denoted "optimal [9]", and the sub-optimal system will be denoted "sub-optimal [9]".

Table 4 Simulation Parameters

Carrier Frequency	2.4 GHz
Bandwidth	20 MHz
Modulation scheme	QPSK, 16-QAM, 64-QAM
Channel encoder	No code, convolutional codes
Channel estimation	Perfect CSI
Number of data subcarrier	64
Guard Interval length	16
Channel model	10-path, Rayleigh Fading
Sample period	0.05μs
Number of data packet	40
Cluster size (N_s)	2, 4, 8, 16, 32

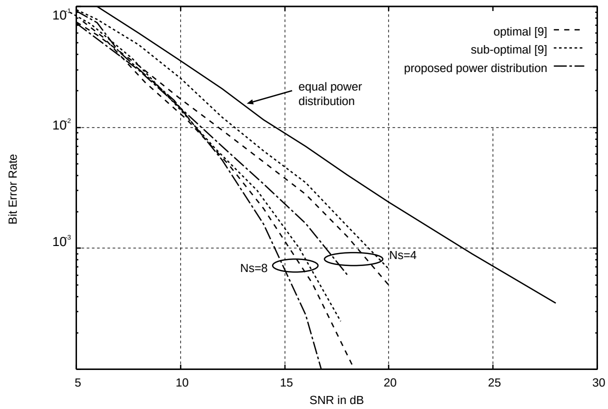

Fig. 3 BER performance for uncoded OFDM with QPSK modulation

4.1 Fixed Modulation

We firstly evaluate the performance of the proposed power allocation scheme for the uniform fixed modulation transmissions, where both modulation level and coding rate are kept constant.

4.1.1 Uncoded OFDM

Fig. 3 shows the BER versus the average total received SNR (dB) of the proposed scheme with QPSK modulation schemes and various subcarrier group sizes N_s. The BER performances of the equal power distribution, the iterative scheme and the BER based suboptimal solution both described in [9] are also plotted in the same figure. According to simulations, at average BER=10^{-3}, 7 and 9 dB gains are respectively obtained for $N_s = 4$ and 8 compared to the equal power distribution scheme. For any group size, the proposed allocation scheme outperforms the optimal and the suboptimal solutions presented in [9]. At BER=10^{-3}, 2 to 3 dB gains are obtained by simply performing the proposed subcarrier selection and ordering followed by the power allocation scheme. Figs. 4 and 5 show the BER performance with 16-QAM and 64-QAM, respectively, for several subcarrier group sizes. From these figures, we can see that the proposed scheme can achieve significant performance gain also for uncoded 16-QAM and

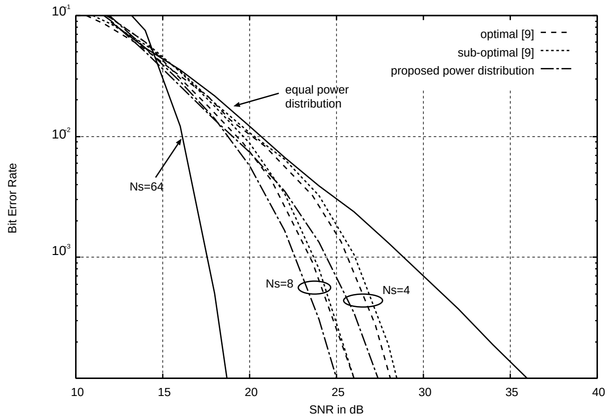

Fig. 4 BER performance for uncoded OFDM with 16-QAM

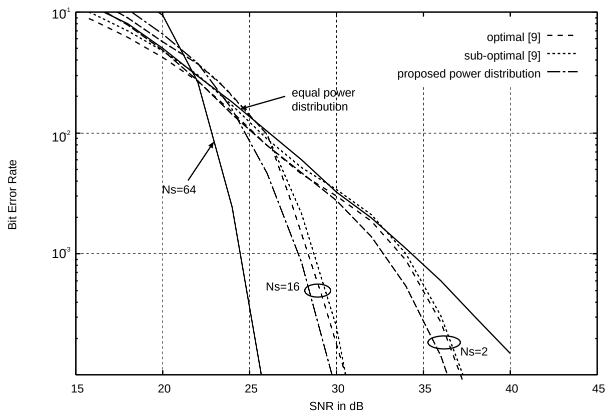

Fig. 5 BER performance for uncoded OFDM with 64-QAM

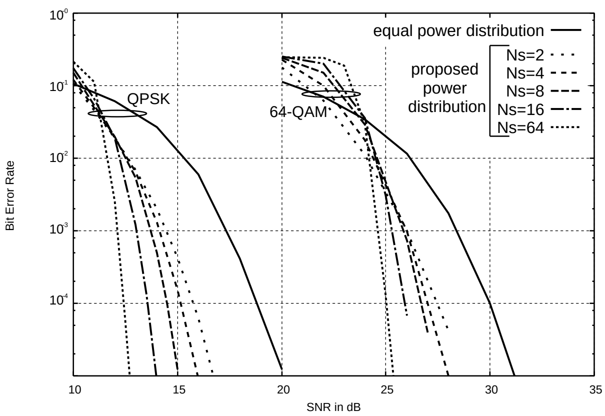

Fig. 6 BER performance of coded OFDM with R=1/2 for QPSK and 64-QAM modulations

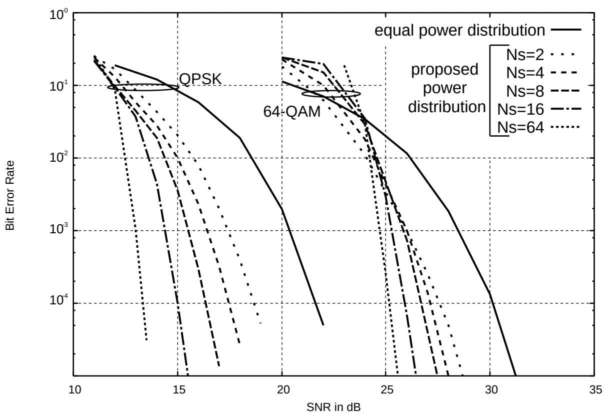

Fig. 7 BER performance of coded OFDM with R=3/4 for QPSK and 64-QAM modulations

64-QAM schemes. Moreover, comparing the performance between the proposed scheme with and without ordering at BER=10^{-3}, 1.5dB gains are obtained on average, for any size of subcarrier grouping (i.e., value of N_s)simply by performing the proposed subcarrier ordering compared to the subcarrier selection proposed in [9]. In addition, due to the structure of the proposed power distribution scheme, the ordering part does not affect the performance of the specific case $N_s = N$. However, due to the structure of the proposed power distribution scheme, there is a trade-off between the subcarrier grouping size and the computational complexity.

4.1.2 Convolutionally Coded OFDM

In Fig. 6, the benefit of performing the proposed scheme is highlighted for the specific case of $R = 1/2$, ZF detection scheme, and QPSK and 64-QAM modulations. The simulation results show that at average BER=10^{-4}, between 4dB and 8dB gains are obtained depending on the subcarrier ordering size (N_s=2, 4, 8, 16, and 64) for QPSK modulation compared to the equal power distribution. In the case of 64-QAM modulation, the proposed power allocation with ordering allows to obtain 3 to 5 dB gains, depending on the size of the subcarrier groups, N_s. The benefit in term of gain for QAM modulation is comparable to that for QPSK modulation. In Fig. 7, impact of the subcarrier grouping size on the results are presented for the QPSK and 64-QAM modulations with $R = 3/4$.

In Figs. 8 and 9 illustrate the benefit of performing the proposed power allocation scheme on coded OFDM system with QAM modulation. Results are presented for a wide range of subcarrier group size, (i.e., N_s) between 2 to 64. The simulation results show that for an average BER=10^{-4}, significant gain are obtained by simply performing the proposed power distribution scheme. In addition, the influence of the subcarrier ordering and subcarrier group size are also highlighted. In the proposed scheme, the impact of the subcarrier group size strongly affects the BER performance. The proposed scheme outperforms the sub-optimal solution presented in [9] also for the coded systems. As a summary, the series of results, presented with computer simulations, highlight the fact that the trade off between the value of the group size and performance

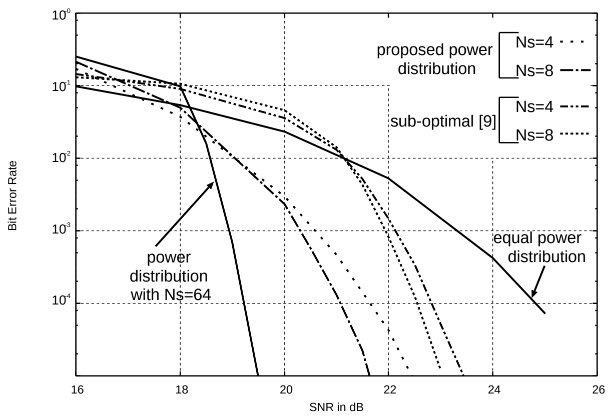

Fig. 8 BER performance for coded OFDM with 16-QAM and $R = 1/2$

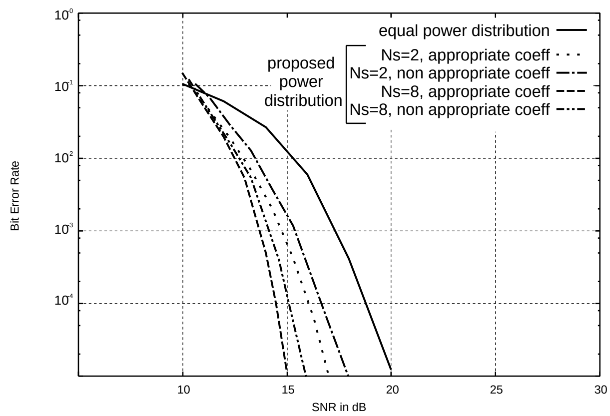

Fig. 10 BER performance for coded OFDM with QPSK modulation using optimized and non-optimized a_m and b_m

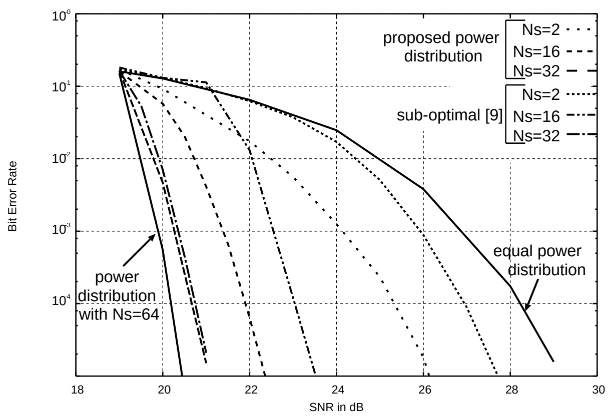

Fig. 9 BER performance for coded OFDM with 16-QAM and $R = 3/4$

should be taken into account to define the most appropriate selection of the parameter N_s.

The BER performance of coded OFDM depends on the correlation among the frequency responses, while, for uncoded case, the BER of each subcarrier is solely determined by the SNR of each subcarrier. This means that the parameters of a_m and b_m for the BER approximation have to be changed depending on the delay spread in practical scenario in order to obtain the best performance by the proposed method. Table 5 shows the parameters obtained by computer simulations for QPSK convolutionally coded ($R = 1/2$) OFDM in 10-path Rayleigh fading exponential decay model with 0.5, 1, and 1.5 dB decaying per sampling period. From the table, we can see that the optimum values of a_m and b_m actually depend on the decaying factor of the channel. Changing the parameters depending on the channel condition, however, may not be practical due to the complexity. Fig. 10 shows the BER performance against the total SNR in dB with optimized and non-optimized coefficients, a_m and b_m. The 10-path Rayleigh fading exponential decay model with 1 dB decaying per sampling period is considered for evaluation. The performance of equal power distribution and the proposed scheme for two group sizes are plotted. Optimized coefficients correspond to $a_m = 7$ and $b_m = 9.5$, whereas the non optimized coefficients correspond the specific channel of 0.5dB decay model (i.e. $a_m = 5.6$ and $b_m = 10.5$). From the figure, we can recognize a certain performance degradation due to the inappropriate parameters for the two different group sizes. However, at BER=10^{-4}, the degradation for non-optimized coefficients is less than 0.8dB for both $N_s = 2$ and $N_s = 8$. Compared to the equal power distribution, at average BER=10^{-4}, respectively 2.5dB and 4dB gains are still obtained by simply performing the proposed scheme even in the case of inappropriate coefficients selection.

4.2 Adaptive Modulation

Figs. 11 and 12 show the BER performances against the total SNR in dB for the adaptive modulation combined with power distribution case, for three different coding gains, R=1/2, 3/4, and 1. For reference, the BER performance of the adaptive modulation scheme without power adaptation is plotted. It consists in selecting the sequence of modulation level that minimizes the heuristic expression of the BER in the specific configuration with equal distribution of the power through the exhaustive search of the OFDM symbol. The minimization is performed through all the subcarrier ($N_s = 64$). For the proposed adaptive modulation and power distribution, the results are presented for two sizes of subcarrier grouping , $N_s = 4$ and 8. Fig. 11 shows signif-

Table 5 Parameters of a_m and b_m: QPSK modulation (Coding Rate: 1/2)

Decaying factor	0.5	1.0	1.5
a_m	5.6	7	7.8
b_m	10.5	9.5	8.9

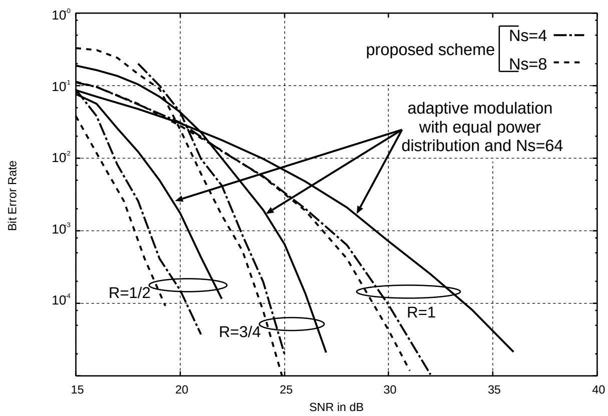

Fig. 11 BER performance for uncoded and coded OFDM with $\overline{B}=3$

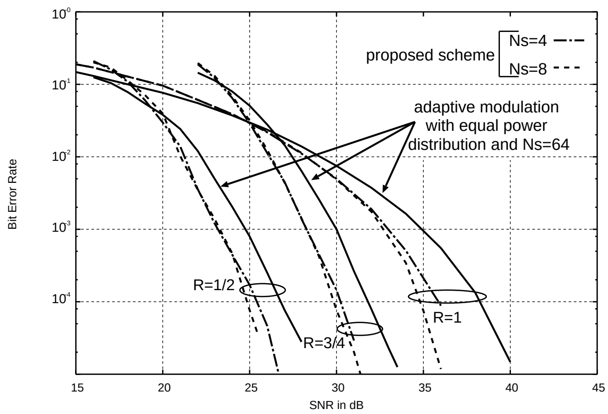

Fig. 12 BER performance for uncoded and coded OFDM with $\overline{B}=5$

icant performance gain by simply performing the proposed power allocation scheme combined with adaptive modulation for an average bits per symbol of 3. At BER=10^{-4} and $R=1$, the average performance gain of 3dB is obtained for the case of $N_s=4$. The performance gain increases to 4dB for the case $N_s=8$. In addition, coding gain does not affect the performance gain of the proposed scheme. A similar gain is obtained for the two sizes of subcarrier grouping for R=1/2 and 3/4. Fig. 12 shows the BER performance for the case that the average number of bits per symbol is equal to 5. A significant performance gain is also obtained by performing the proposed adaptive modulation and power allocation scheme. 2.5dB gain is obtained, on average, for the different coding gains and $N_s=4$. However, these results highlight the limited gain performed by large sizes of subcarrier groups. The difference of the gain is only 1dB between $N_s=4$ and $N_s=8$ for the case of $R=1$ and only 0.5dB gain is obtained which is low, compared to the coding gains for R=1/2 and 3/4.

5. Conclusion

This paper proposes a novel scheme for OFDM that adapts both the modulation scheme and the transmit power in the frequency domain using a heuristic expression of the BER for each subcarrier. A closed form expression of the optimum power to be allocated for each subcarrier is presented for uncoded OFDM transmission as well as coded scheme. The proposed scheme allows to reduce the computational complexity, by including a subcarrier grouping method with local power adaptation for each subcarrier group. Our subcarrier grouping method minimizes the adverse impact of the local power adaptation by taking into consideration the channel gains of all the subcarriers. The characteristics allow us to control the trade-off between the transmission performance and the computational complexity by adjusting the sizes of subcarrier groups. The simulation results show significant improvement of BER performance both in the uncoded and coded cases for QPSK and QAM modulations compared to the equal power allocation scheme. In this paper, we have limited the channel coding scheme to the convolutional code. However, other powerful coding schemes such as the Turbo Codes (TC) [19] or Low Density Parity Check (LDPC) [20]-[21], with appropriate consideration on the impact of the number of information bits per frame due to the interleaver depth on the BER performance, can also be included in the modulated transmission. Finally, future orientation for this work would include the introduction of the error in the channel estimation [22].

Acknowledgment

The authors would like to thank Dr. Yukou Mochida and Mr. Jerome Laudouar of France Telecom R&D Tokyo for their valuable discussions and supports.

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