FREQUENCY DOMAIN POWER ADAPTATION SCHEME FOR MULTI-CARRIER SYSTEMS

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ABSTRACT

Multi-carrier modulation (MCM) scheme such as Orthogonal Frequency Division Multiplexing (OFDM), is a popular method for high data rate wireless transmission. This paper proposes a novel transmit power allocation for MCM. This technique consists of adapting the power allocation in the frequency domain by considering the channel variations. Optimization process is based on the optimality of the global Bit Error Rate (BER). Simulation results show significant gains for several modulations and setting configurations.

Keywords- Multi-carrier Modulation, Lagrangian method, global BER optimization.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has recently been applied widely in wireless communication systems due to its high data transmission capability with high bandwidth efficiency. Robustness to multi-path delay is obtained when appropriate guard interval such as cyclic prefix (CP) or zero padding (ZP) is inserted in the transmitted frame. In frequency selective fading environment, fading conditions strongly affect the channel gains of each subcarrier. In this publication, we propose to adapt the transmit power in the frequency domain in terms of bit error rate (BER) performance subcarrier-per-subcarrier. The proposed method consists of grouping a certain number of subcarriers and then perform local power adaptation in each subcarrier group. The rest of the paper is organized as follows. In Section II we review the conventional Multi-Carrier Modulation scheme. In Section III, we introduce the estimate value of BER for channel encoded sequence and we describe in detail the proposed power adaptation scheme in the frequency domain. Grouping method and calculation of the power allocation in the frequency domain will be explained. Section IV gives the experimental results over QPSK and QAM modulations and several coding gains. Finally, conclusions are drawn in Section V.

II. OFDM SIGNAL

The principle of OFDM transmission scheme is to reduce bit rate of each sub-carrier [1] and also to provide high bit rate transmission by using a number of those low bit rate subcarriers. Frequency bandwidth is divided into small ranges and each of them is handled by these low rate subcarriers. The subcarriers are orthogonal to each other. To obtain this property, the subcarrier frequencies must be spaced by a multiple of the inverse of symbol duration. Multi-carrier modulation system can provide immunity against frequency selective fading because each carrier goes through non-frequency selective fading. However, the channel must be estimated and corrected for each subcarrier.

A. OFDM transmitter

The High-speed binary data are first encoded (convolution coding) and modulated (QPSK, 16-QAM or 64-QAM). Then data are converted to parallel low speed modulated data streams and fed to several subcarrier channels. The modulated signals are frequency-division multiplexed by a N-point inverse discrete Fourier transform (IDFT). The resulting OFDM signal is then converted into an analog signal by a digital-analog (D/A) converter, up-converted (U/C) to the RF band and transmitted in air. For reliable detection, it is typically necessary that the receiver knows the wireless communication channel and keeps track of phase and amplitude variations. To enable the estimation of the wireless communication channel, the transmitter occasionally sends known training symbols. For instance, a preamble, which includes channel training sequences, is added to every packet in IEEE 802.11 WLAN standards [2]-[3]. Consider an OFDM system that transmits N modulated data symbols in the i-th OFDM symbol period through N subchannels. For the i-th block symbol, the transmitted baseband OFDM signal is expressed as [4]:

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

where $x_{i,k}$ is the modulated data symbol of the i-th OFDM symbol. To combat ISI and Inter Carrier Interference (ICI), Guard Interval (GI) [5] such as Cyclic Prefix (CP) or Zero Padding (ZP) is added to the OFDM symbols. In the case of CP, the last N_g samples of every OFDM symbol are copied and added to the heading part. The transmit signal can be described as follow:

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

B. OFDM receiver

At the receiver, signals are passed through a down-converter (D/C) and a digital to analog converter with rate 1/Ts. Then, the GI is removed and the N-point Discrete Fourier Transform (DFT) is performed. Since channel parameters suppose to be frequency selective, detection has to be done per subcarrier. Finally, de-mapping, de-interleaving and channel decoding are performed on the data streams and the resulting data are combined to obtain the original binary sequence.

C. *Channel representation and detection scheme*

We assume that the system is operating in a frequency selective Rayleigh fading environment [6] and the communication channel remains constant during a packet transmission. Data frame duration is assumed to transmit within the coherent time of the wireless system. In this case, channel variations remain constant during on frame transmissions and may change between consecutive frame transmissions. We suppose that the fading channel can be modeled by a discrete-time baseband equivalent $(L-1)$-th order finite impulse response (FIR) filter where L represents time samples corresponding to the maximum delay spread. In addition, an additive white Gaussian noise (AWGN) with independent and identically distributed (iid) zero mean, complex Gaussian elements is assumed. When the maximum delay spread does not exceed GI, since ISI does not occur on OFDM symbol basis, the frequency domain OFDM signal after removal of GI is described by:

$$y_{j,m} = h_m . x_{j,m} + n_{j,m} \tag{3}$$

where $y_{j,m}$ is the received signal for the j-th OFDM symbol and the m-th subcarrier and h_m is the channel parameter for the m-th subcarrier. In addition, $n_{j,m}$ denotes the additive Gaussian noise. Thus it results in a frequency-flat-fading signal model per subcarrier. For simplicity, without losing any generality, we will omit writing the index for both the subcarrier and the symbol indicators.
Channel correction is simply realized by multiplying on each subcarrier the inverse of the channel coefficient. Channel equalization can be described by:

$$g_m = \frac{h_m^*}{|h_m|^2} \tag{4}$$

In the Zero Forcing (ZF) linear detector, the received signal is multiplied with a filter which is the inverse of the channel response.

III. Power Allocation Scheme

A. *Bit Error Rate approximation*

We next list the assumptions adopted in this paper. The channel is frequency flat, and remains invariant per frame, but is allowed to vary from frame to frame. This corresponds to a block fading channel model, which is suitable for slowly-varying channels. As a consequence, power allocation is adjusted on a frame-by-frame basis. Perfect channel state information (CSI) is available at the receiver. The corresponding power selection is fed back to the transmitter without any error and latency. The assumption that the feedback channel is error free and has no latency, could be at least approximatively satisfied by using a fast feedback link with powerful error control for feedback information. Further considerations on system design with delayed or noisy CSI will be in the future considered.
For flat fading channel adhering the previous assumptions, the channel characteristics is captured by the received SNR. The received SNR is a function of the variance of the noise, the channel state information, and the transmit power. Since the channel varies from frame by frame, the approximated BER can be described as a function of the received SNR (i.e. transmit power for each transmit antenna and channel condition). In [7], a general formula describing this relation in a flat fading channel environment is proposed. Typically, the BER for any modulation can be simply estimated as follows:

$$f(\beta_m, p_m) \approx a \times \exp\Big\{ -b \times \beta_m \times p_m \Big\} \tag{5}$$

with:

$$\beta_m = \frac{1}{(2^{N_m}-1).\sigma_n^2.|g_m|^2} \tag{6}$$

where N_m, σ_n^2, and p_m are respectively the number of bits per symbol, the variance of the noise and the transmit power on the m-th subcarrier.
Table I summarizes the heuristic value of the parameters a and b defined in (5) for several modulations. Parameters are obtained by fitting (5) to simulated data.

Table 1: Transmission modes for different modulation

Modulation	QPSK	16-QAM	64-QAM
Rate (bits/symb.)	2	4	6
a	0.2	0.2	0.15
b	1.66	1.73	1.68

B. *Proposed principle*

The basic principle of the frequency domain power allocation for multi-carrier signal is to perform frequency domain optimization of the transmit power in function of the channel state information (CSI) and the expression of the global BER for the different modulations. By simply performing transmit power allocation from the estimate value of the BER, we propose to optimize the transmit power allocation by performing Lagrangian method on the BER expression. Constraint is added in order to keep constant the global transmit power at the transmitting part. We propose to combine different load subcarrier in order to optimize the power allocation without increasing a lot the complexity. Generally, channel variations between consecutive subcarriers are smooth. Major impact of this property is that in a strong fading environment consecutive subcarriers are strongly affected by the channel conditions. In order to take maximum advantage of the optimization structure, we propose to split into two parts the global optimization of the power allocation, at the transmitting part. To take advantage of the frequency domain selectivity, we propose to first group subcarriers which are affected by strong fading with subcarriers which are not so much faded. One possible criterion to evaluate the impact of the fading in the frequency domain is the power value of the channel coefficients, denoted $|h_m|^2$. We denote N_{cl} the group size of the power allocation in the frequency domain (i.e. size of the subset of subcarrier on which optimization is performed). First, using the information of the channel in the frequency domain, N_{cl} subcarriers are selected

and then power allocation scheme is performed on them. Then, the specific values of the power allocation is saved and index of the N_{cl} and the associate power coefficients are eliminate of the set of processed subcarriers. Selection and power allocation method are repeated N/N_{cl} times. For the proposed scheme, N_{cl} needs to be a multiple of N.
Fig. 1 illustrates the principle to group the different N_{cl} subcarriers.

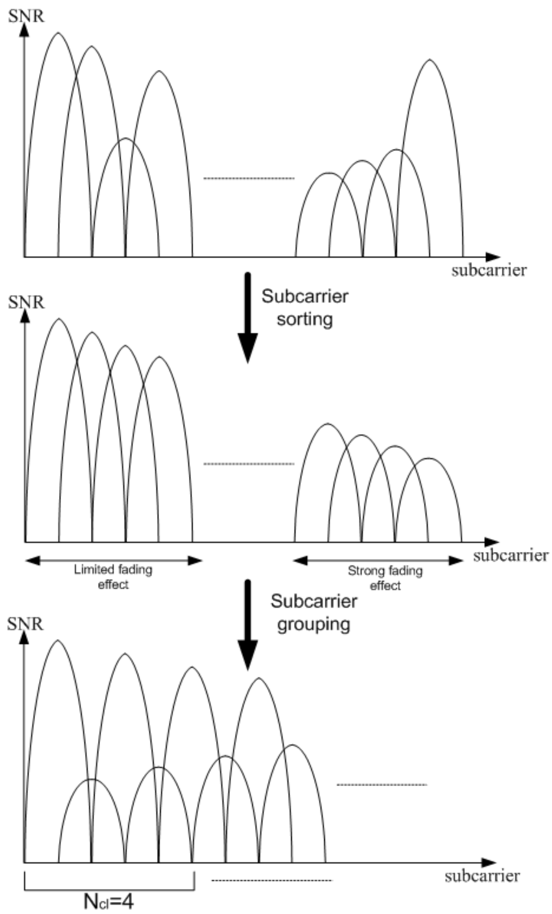

Figure 1: Principle of the group selection in function of the fading effect

C. Mathematical description

Proposed power allocation consists of optimizing the BER function described below by estimating optimum power allocation [8]. Power allocation algorithm determines how to allocate the power in the frequency domain. The global power resource assigned by the proposed algorithm satisfies the simple relation that the total transmit power is kept constant. Principle is described in this section for one set of subcarrier. In practical implementation (i.e. for simulation), proposed method are repeated N/N_{cl} times. This constraint for each selected subset of size N_{cl} can be described by:

$$\sum_{m=0}^{N_{cl}-1} p_m = N_{cl}.\overline{P} \tag{7}$$

where $\overline{P}_m$ denotes the average Transmit Power on the subcarrier m and N_{cl} represents the size of the cluster.
The average BER becomes minimal when the BER is minimized for each given channel state. Equivalent mathematical representation can be given by:

$$\begin{cases} \min f(\beta_m, p_m) \\ \text{subject to:} \\ \sum_{l=0}^{N_{cl}-1} p_m = N_{cl}.\overline{P} \end{cases} \tag{8}$$

One possibility to solve this optimization problem is to apply the Lagrangian procedure on each cluster. The processing can be described as:

$$\begin{aligned} J(p_0, ..., p_{N_{cl}-1}) &= \frac{1}{N_{cl}} \sum_{l=0}^{N_{cl}-1} f(\beta_m, p_m) \\ &+ \lambda \times \left(\sum_{l=0}^{N_{cl}-1} p_m - N_{cl} \times \overline{P} \right) \end{aligned} \tag{9}$$

Then, optimal solutions are obtained by solving for each transmit antenna:

$$\begin{cases} \frac{1}{N_{cl}}.\frac{\partial}{\partial p_m}\left(\sum_{l=0}^{N_{cl}-1} f(\beta_m, p_m) \right) + \lambda = 0 \\ \sum_{l=0}^{N_{cl}-1} p_m - N_s.\overline{P} = 0 \end{cases} \tag{10}$$

By introducing the explicit estimation of the BER in the set of equations, we can write for each transmit antenna that:

$$\begin{cases} \frac{-a.b.\beta_m}{N_{cl}} \times \exp(-b.\beta_m.p_m) + \lambda = 0 \\ \sum_{l=0}^{N_{cl}-1} p_m - N_{cl}.\overline{P} = 0 \end{cases} \tag{11}$$

After calculation and rearrangement, we finally obtain the following general solution:

$$\begin{aligned} p_m &= \left[1 + \sum_{\substack{u=0 \\ u \neq m}}^{N_{cl}-1} \frac{\beta_m}{\beta_u} \right]^{-1} \\ &\times \left[N_{cl}.\overline{P} + \frac{1}{b} \times \sum_{\substack{u=0 \\ u \neq m}}^{N_{cl}-1} \frac{1}{\beta_u} \times \log\left(\frac{\beta_m}{\beta_u} \right) \right] \end{aligned} \tag{12}$$

Due to the specificity of the Lagrangian calculation (only mathematical solutions are obtained), we need to add a constraint when the output of the Lagrangian optimization does not reflect any physical solution, typically when we obtain: $p_m \leq 0$. In this case we propose to apply the conventional scheme.
We repeat the power allocation process for each cluster of subcarrier which composes the OFDM symbol.
Algorithm 1 summarizes the general principle which consists of selecting N_{cl} subcarriers, then performing optimization and finally repeating the optimination N/N_{cl} times.

Algorithm 1
Sorting, selecting subcarrier assignment
and performing power allocation

Repeat N/N_{cl} times
Step1
$N_{cl}/2$ subcarriers which supports strong
fading effects of the $N_{cl}/2$
subcarriers which supports limited fading effects

Step2
Combine the different elements defined in step 1

Step3
Perform the optimization through the N_{cl} elements

Step4
Eliminate the elements which have been
used for optimization using Eq. 12
Repeat the step 1, 2, and 3
End of Repeat

IV. Experimentation

We now evaluate the performance of the proposed power allocation method for multi-carrier scheme in a mutli-path fading environment. Main simulation parameters are introduced in the Table II. We assume perfect knowledge of the channel variations both at the transmitting and receiving parts. For all simulations, an exponential model with 1-dB decay multi-path model is assumed. Carrier frequency is equal to 2.4GHz, the IFFT/FFT size is 64 points and the guard interval is set up at 16 samples. Effect of proposed scheme for several cluster sizes and different modulations is highlighted.

Table 2: Simulation Parameters

Carrier Frequency	2.4 GHz
Bandwidth	20 MHz
Modulations	QPSK, 16-QAM, 64-QAM
Channel encoder	No code
Channel estimation	Perfect CSI
Number of data subcarrier	64
Guard Interval length	16
Channel model	5-path, Rayleigh Fading
Sample period	0.05μs
Number of data packet	50
Cluster size (N_{cl})	2, 4, 8

Fig. 2, 3 and 4 show the Bit Error Rate (BER) versus the average total received SNR (dB) for different modulations and cluster sizes. Both conventional and proposed schemes are plotted in these figures and results are presented for ZF detection scheme.

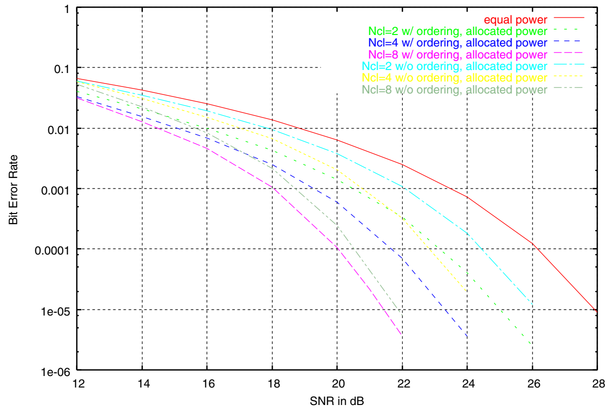

Figure 2: Performance Simulation for QPSK modulation

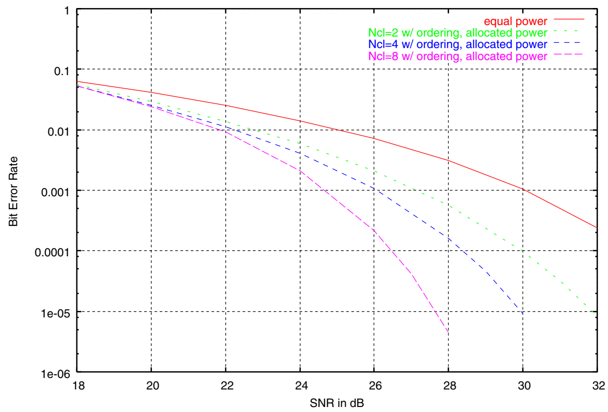

Figure 3: Performance Simulation for 16-QAM modulation

In the Fig. 2, the benefit of performing the proposed scheme is highlighted for the case QPSK modulation and ZF detection scheme. Simulation results show that at average BER=10^{-5}, respectively 3dB, 5dB and 7dB gains are obtained for $N_{cl} = 2$, $N_{cl} = 4$ and $N_{cl} = 8$ when power allocation with ordering is employed.

In addition, impact of the ordering is also highlighted in this figure. Respectively 0.5dB, 0.7dB and 0.9dB gains are obtained when we compare the proposed scheme with and without ordering for three different cluster sizes. Combining the different values of the selective fading between performing the power allocation is beneficial in term of BER. As detail in III.B, ordering part is set up by comparing the value of the fading for each carrier. Proposed selection and ordering is based on the value of the channel.
It is shown that impact of the cluster size strongly affects the quality of the proposed scheme. In parallel, (12) shows the exact value of the method to estimate the specific power allocation depends on the cluster size, N_{cl}. Combining the complexity of the method with the performance shows that trade-off between performance and complexity should be estimated.

In the Fig. 3, results are presented for the case 16-QAM

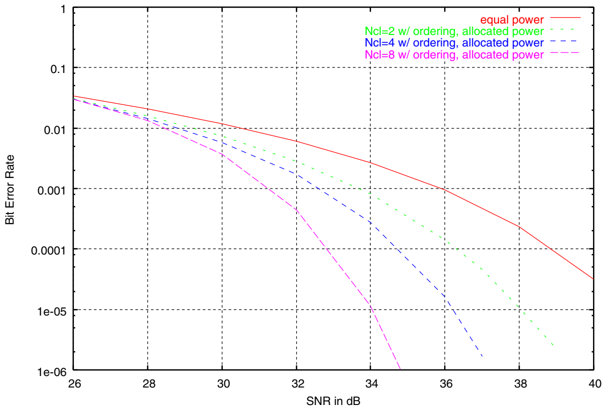

Figure 4: Performance Simulation for 64-QAM modulation

modulation for different cluster sizes. Gain obtained by performing proposed power allocation scheme with ordering becomes equal to 2.8dB for $N_{cl} = 2$, 4.4dB for $N_{cl} = 4$ and 6.4dB for $N_{cl} = 8$ at average BER=10^{-4}.

Average BER versus the total SNR are presented in the Fig. 4 for the case 64-QAM modulation. Gain obtained by performing proposed power allocation scheme becomes relatively significant. At average BER=10^{-4}, 3dB for $N_{cl} = 2$, 4.5dB for $N_{cl} = 4$ and 6.2dB for $N_{cl} = 8$ gains are obtained.

For the different modulations, complexity of the power allocation method proposed in this publication depends on the size of the cluster and also the ordering part which is especially highlighted in Fig. 2. Larger is the cluster size and better is the BER performance of the OFDM transmission. However, both performance and complexity of the power allocation method strongly depend on the cluster size and the ordering method.

V. Conclusion

In this paper, a novel power allocation processing for Multi-Carrier based transmission has been presented. The basic procedure consists of allocating transmit power in function of the channel conditions and the global BER requirement. The simulation results have shown promising results in term of BER for several sets of cluster configuration and different modulations. Extension of the proposed power allocation scheme can be easily proposed to no-linear detection scheme such as the Maximum Likelihood Detection (MLD) scheme as in [9]. Finally, results including channel encoding can be extended to convolutional codes. Other powerful encoder like the Turbo Codes (TC) [10] or Low Density Parity Check (LDPC) [11] 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 [12]. For all these different modifications, adaptation of the analytical value of the BER must be updated.

Acknowledgment

The authors would like to thank Mr. Haruo Mio of FT R&D Tokyo and Dr. Patrick Tortelier FT R&D for their valuable discussions.

References

[1] L.J. Cimini., "Analysis and simulation of digital mobile channel using orthogonal frequency division multiple access," *IEEE Tans. Commun.*, pp.665–675, 1995.

[2] IEEE 802.11a standard, ISO/IEC 8802-11, 1999.

[3] Draft IEEE 802.11g standard, Further Higher Speed Physical Layer Extension in the 2.4GHz Band, 2001.

[4] R. Van Nee et al., OFDM for wireless multimedia communications, Artech House, 2000.

[5] B. Muquet et al., "Reduced complexity equalizers for zero-padded OFDM transmissions," *Proc. of the ICASSP*, Istanbul, Turkey, 2000.

[6] J. Proakis, Digital Communications, 3rd ed. Singapore: McGraw-Hill, 1995.

[7] X. Qiu et al., "On the performance of adaptive modulation in cellular system," *IEEE TRANS. On Communications*, vol.47, no.6, pp.884–895, 2005.

[8] Zh. Jiang et al., "Max-Utility wireless resource management for best-effort traffic," *IEEE Wirel. Commun. Mag.*, vol.4, no.1, pp.100–111, 2005.

[9] H. Kawai et al., "Likelihood Function for QRM-MLD Suitable for Soft-Decision Turbo Decoding and Its Performance for OFCDM MIMO Multiplexing in Multipath Fading Channel," *IEICE Trans. Commun. Mag.*, vol.E88, no.1, pp.47–57, 2005.

[10] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near shannon limit error-correcting coding and decoding: Turbo-codes," *in Proc. IEEE International Conference on Communications (ICC'93)*, Geneva, Switzerland, May 1993, pp. 1064–1070.

[11] R. Gallager, "Low Density Parity Check codes," *Cambridge, MIT press*, 1963

[12] G. E. Oien, H. Holm, and K. J. Hole, "Adaptive Coded Modulation With Imperfect Channel State Information: System Design and Performance analysis Aspects," *in Proc. IEEE Int Symposium Advances in Wireless Communications*, Victoria, Canada, pp.19–24, Sept. 2002.