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Low Complexity Precoded Greedy Power Allocation Algorithms for OFDM Communication Systems

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ABSTRACT

In this paper, an enhanced greedy bit and power allocation algorithms for orthogonal frequency division multiplexing (OFDM) communication systems are introduced. These algorithms combine low complexity greedy power allocation algorithms with a simplified maximum ratio combining (MRC) precoding technique at the transmitter for maximizing the average data throughput of OFDM communication systems. Results of computer simulations show that precoding is an effective technique for improving the throughput performance of the proposed bit and power allocation algorithms.

Keywords: OFDM; Uniform Power Allocation; Greedy Algorithm; Throughput Enhancement; MRC Precoding

1. Introduction

Multicarrier modulation (MCM) is a powerful transmission technique that provides improved performance in various communication fields; it introduces important benefits as efficient bandwidth optimization, enhanced spectrum utilization, low equalization complexity, and multiuser potentiality. Moreover, it is widely used in new application fields, such as power line communications (PLC) [1-3], and wireless local area networks (WLANs) [4-6] due to its recognized value to confront various channel impairments, including frequency selectivity, intersymbol interference (ISI), and impulse noise.

Two important MCM techniques that have wide spread use are OFDM [6] mainly employed in wireless applications, and discrete multitone (DMT) [7] used in wireline systems. In conventional wireless OFDM systems, all subcarriers employ the same signal constellation. However, the overall error probability is dominated by the subcarriers with the worst performance. To improve system performance and throughput, adaptive bit and power allocation algorithms can be employed, where the signal constellation size and power distribution vary according to the measured signal-to-noise ratio (SNR) values across the subcarriers [8].

The bit and power allocation is a constraint optimization problem, and generally two cases are of practical interest; rate maximization (RM) and margin maximization (MM), where the objective is the maximization of the achievable data rate or the achievable system margin, respectively. A rate-optimal algorithm known as the greedy power allocation (GPA) algorithm [9,10], of which a number of different variations have emerged constraining either the average bit error rate (BER) [8] or the total power [11]. For a good review of greedy algorithms, please refer to [1]. Suboptimal GPA algorithms, whereby the bit and power re-allocation are performed in groups of subcarriers are proposed in [12], resulting in low complexity algorithms compared with the GPA algorithm.

An MRC precoding technique is proposed to enhance the low complexity GPA algorithms proposed in [12] for OFDM signal transmission in hostile environments and to simplify receiver complexity by transferring the signal processing to the transmitter. For high speed communications, the channel is changing faster than it can be estimated and fed back to the transmitter. So adaptive bit and power allocation algorithms perform poorly. Other means for mitigating the effect of fading should be used [13]. In this paper, enhanced adaptive bit and power allocation algorithms for OFDM communication systems are introduced. These algorithms combine low complexity bit and power allocation algorithms and a simplified precoding technique at the OFDM transmitter for data throughput enhancement. The proposed system operates in time division duplex (TDD) mode in which the channel reciprocity between alterative uplink and downlink transmissions is exploited to feed the channel state information (CSI) back to the transmitter side.

The rest of this paper is organized as follows. In Section 2, the problem of bit and power allocation for OFDM system is overviewed. The proposed bit and power allocation algorithms are described in Section 3. Simulation results are given in Section 4. Finally, con-

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clusions are given in Section 5.

2. Bit and Power Allocation for OFDM System

OFDM is a promising technique for achieving the high data rate transmission required for wireless multimedia services over time dispersive multipath channels [14]. To improve the OFDM system throughput, adaptive bit and power allocations are employed.

2.1. Problem Definition

The problem of the maximization of the transmission rate over the OFDM wireless system is considered, where the multipath channel characterized by a finite impulse response (FIR) vector $h=\left[h_0\ h_1\cdots h_L\right]$ of order L is converted to an N-subcarriers system with different gains g_n, $n=1,2,3,\cdots,N$. The n^{th} subcarrier experiencing the gain g_n will be used to transmit b_n bits per symbol. The following constrained optimization problem must be solved to determine the optimum bit and power allocations to maximize the OFDM system throughput

$$\max\sum_{n=1}^{N} b_n \qquad \text{subject to}$$

$$\sum_{n=1}^{N} p_n \le p_t,\ p_{e,n}=p_e^{\text{target}},\ \text{and}\ b_n \le b^{\max},\ \forall n \quad (1)$$

where b_n and p_n are the bit and power allocated to the n^{th} subcarrier to achieve a bit error rate (BER) of $p_{e,n}$, p_t is the total power budget, and $b^{\max}$ is the maximum number of permissible allocated bits per subcarrier .

The n^{th} subcarrier power to noise ratio can be defined as follows:

$$\text{CNR}_n=\frac{g_n^2}{N_0} \quad (2)$$

where N_0 is the noise power at the receiver, and the SNR of this subcarrier is

$$\gamma_n = p_n\times\text{CNR}_n \quad (3)$$

Symbols of b_k-bits, $b_k=\log_2 M_k$ can be loaded to the subcarrier with the minimum required SNR γ_k^{QAM} [12,15] of

$$\gamma_k^{\text{QAM}}=\begin{cases}\dfrac{\left[Q^{-1}\left(P_e\right)\right]^2}{2} & \text{for BPSK}\\ \dfrac{M_k-1}{3}\left[Q^{-1}\left\{\dfrac{1-\sqrt{1-\log_2 M_k P_e}}{2\left(1-1/\sqrt{M_k}\right)}\right\}\right]^2 & \text{for M-ary QAM}\end{cases} \quad (4)$$

where M_k is the maximum permissible QAM constellation by the transmission system and Q^{-1} is the inverse of a well-known Q function that is the tail probability of the standard normal distribution [15]. The solution of the constrained optimization problem in (1) can be divided into two steps, uniform power allocation (UPA) initialization step and the GPA algorithm. Both of them are described below.

2.2. Uniform Power Allocation (UPA) Algorithm

The steps of UPA algorithm can be summarized as follows [12]:

1) Calculate γ_k^{QAM} for all M_k, $1\le k\le K$ and the target BER $P_e=P_e^{\text{target}}$ using (4).

2) Allocate the total power budget p_t between all subcarriers, equally, as follows

$$\gamma_n = P_n\times\text{CNR}_n=\frac{P_t}{N}\times\text{CNR}_n \quad (5)$$

3) Redistribute subcarriers according to their SNRs γ_n into QAM groups G_k, $0\le k\le K$ bounded by QAM levels γ_k^{QAM} and $\gamma_{k+1}^{\text{QAM}}$ with $\gamma_0^{\text{QAM}}=0$ and $\gamma_K^{\text{QAM}}=+\infty$ *i.e.* $\gamma_k^{\text{QAM}}\le\gamma_n<\gamma_{k+1}^{\text{QAM}}$

4) Load subcarriers within each G_k group with QAM constellation M_k such that the total allocated bits of this group is

$$B_k^{\text{UPA}}=\sum_{n\in G_k} b_{n,k}^{\text{UPA}}=\sum_{n\in G_k}\log_2 M_k \quad (6)$$

with $B_0^{\text{UPA}}=0$ and the total excess power for this group

$$P_k^{\text{excess}}=\sum_{n\in G_k}\frac{\left(\gamma_n-\gamma_k^{\text{QAM}}\right)}{\text{CNR}_n} \quad (7)$$

5) The total number of the system allocated bits and the used power for the UPA algorithm are

$$B_{\text{UPA}}=\sum_{k=1}^{K} B_k^{\text{UPA}} \quad (8)$$

$$P_{\text{UPA}}^{\text{used}}=P_t-P^{\text{excess}}=P_t-\sum_{k=1}^{K}P_k^{\text{excess}} \quad (9)$$

The total excess power produced by the UPA algorithm is well exploited by a number of algorithms, and this represents a useful indication about the efficient utilization of the total transmit power P_t.

2.3. Full Greedy Power Allocation (GPA) Algorithm

The GPA algorithm [1,9,10,12] is based on the initialization step described above. This algorithm performs an iterative re-distribution of the excess power of the UPA algorithm. Applying the steps described in **Table 1**, resulting in an overall system allocated bits and used power given, respectively, by

$$B_{\text{GPA}}=\sum_{n=1}^{N} b_n^{\text{GPA}} \quad (10)$$

and

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Table 1. Full GPA algorithm.

Step	Operation
Input	b_n^{UPA}, P^{excess}, CNR_n
Initialization	• Set power of GPA $P_d^{\text{GPA}} = P^{\text{excess}}$ in (7) • For each subcarrier *n* do the following: 1) Set $b_n^{GPA} = b_n^{UPA}$ 2) Initiate $k_n = k$ in (7) 3) Calculate the min. required upgrade power: $P_n^{\text{up}} = \frac{\left(\gamma_{k_{n+1}}^{\text{QAM}} - \gamma_{k_n}^{\text{QAM}}\right)}{\text{CNR}_n}$
Recursion	While $P_d^{\text{GPA}} \geq \min\left(p_n^{\text{up}}\right)$ and $\min\left(k_n\right) < K$ $j = \arg\min\left(p_n^{\text{up}}\right), 1 \leq n \leq N$ $k_j = k_j + 1$, $P_d^{\text{GPA}} = P_d^{\text{GPA}} - P_j^{\text{up}}$ If $k_j = 1$ $b_j^{\text{GPA}} = b_j^{\text{GPA}} + \log_2 M_2$, $P_j^{\text{up}} = \frac{\left(\gamma_{k_{n+1}}^{\text{QAM}} - \gamma_{k_n}^{\text{QAM}}\right)}{\text{CNR}_n}$ else if $k_j < K$ $b_j^{\text{GPA}} = b_j^{\text{GPA}} + \log_2\left(\frac{M_{k_j}}{M_{k_{j-1}}}\right)$, $P_j^{\text{up}} = \frac{\left(\gamma_{k_{j+1}}^{\text{QAM}} - \gamma_{k_j}^{\text{QAM}}\right)}{\text{CNR}_n}$ else $b_j^{\text{GPA}} = b_j^{\text{GPA}} + \log_2\left(\frac{M_{k_j}}{M_{k_{j-1}}}\right)$, $P_j^{\text{up}} = +\infty$ end end $B_{\text{GPA}} = \sum_{n=1}^{N} b_n^{\text{GPA}}$
Output	B_{GPA}, P_d^{GPA}

$$P_{\text{GPA}}^{\text{used}} = P_t - P_d^{\text{GPA}} \tag{11}$$

3. The Proposed Pre-Coded Bit and Power Allocation Algorithms

Bit and power allocation algorithms for OFDM systems with equalization at the receiver have been studied in the literature. However, applying bit and power allocation algorithms with pre-coding techniques is still new, and there are a lot of open issues. In this paper, hybrid algorithms comprising the low complexity bit and power allocation algorithms in [12] and a pre-coding technique [16] will be proposed and studied.

3.1. MRC Pre-Coding Technique

A MRC pre-coding is proposed for enhancing the bit and power allocation of OFDM system as shown in **Figure 1**, where it is based on correcting the phase and weighting the amplitude of each subcarrier [16]. The signal model of MRC Pre-coded OFDM system is described as follows

$$\boldsymbol{R} = \boldsymbol{\Lambda}^H \boldsymbol{\Lambda} \boldsymbol{X} + \boldsymbol{W} \tag{12}$$

where $\boldsymbol{R}$ is the $N \times 1$ received signal vector, $\boldsymbol{\Lambda}$ is an $N \times N$ diagonal channel matrix containing the frequency domain channel coefficient of each subcarrier, $\boldsymbol{\Lambda}^H$ is $N \times N$ complex conjugate transpose of $\boldsymbol{\Lambda}$, $\boldsymbol{X}$ is an $N \times 1$ transmitted signal vector, and $\boldsymbol{W}$ is an $N \times 1$ additive white Gaussian noise (AWGN) vector. The n^{th} subcarrier gain g_n in (2) is replaced by MRC pre-coded n^{th} subcarrier gain $\left|\boldsymbol{\Lambda}_n^H \Lambda_n\right|$. Based on the new pre-coded channel coefficients described above, UPA algorithm is re-applied to determine new subcarriers bit allocation $B_k^{\text{pre-UPA}}$ and new total excess power P_k^{excess} for each QAM level group as defined in (6) and (7), respectively. Three enhanced low-complexity greedy algorithms are proposed and studied to efficiently utilize the new total excess power of the Pre-UPA algorithm. These algorithms are Pre-coded QAM-Level GPA (Pre-LGPA) algorithm, Pre-coded Power Moving up GPA (Pre-MuGPA) algorithm, and Pre-coded Power Moving down GPA (Pre-MdGPA) algorithm.

3.2. Pre-LGPA Algorithm

The direct application of the GPA algorithm is computationally very complex, because at each iteration, exhaustive sorting and searching algorithms of all subcarriers are required as shown in **Table 1**. A simplified technique of the GPA algorithm can be obtained if the subcarriers are firstly divided into QAM groups G_k, $0 \leq k \leq K$ according to their SNRs.

The GPA algorithm is therefore independently applied to each group G_k. The Pre-LGPA algorithm is well described in **Table 2** where it permits upgrading to the next QAM level only and therefore may leave some left-over power P_k^{LO} for each QAM group G_k, resulting in a total left-over power of

$$P_{\text{pre-LGPA}}^{LO} = \sum_{k=0}^{K-1} P_k^{LO} + P_K^{\text{excess}} \tag{13}$$

The Pre-LGPA algorithm has to be executed *K* times, once for each QAM group resulting in an overall system that allocates bits and power according to

$$B_{\text{pre-LGPA}} = \sum_{k=0}^{K-1} B_k^{\text{pre-LGPA}} + B_K^{\text{pre-UPA}} \tag{14}$$

and

$$P_{\text{pre-LGPA}}^{\text{used}} = P_t - P_{\text{pre-LGPA}}^{LO} \tag{15}$$

3.3. Pre-MuGPA Algorithm

The Pre-LGPA algorithm results in an unused P_k^{LO} for

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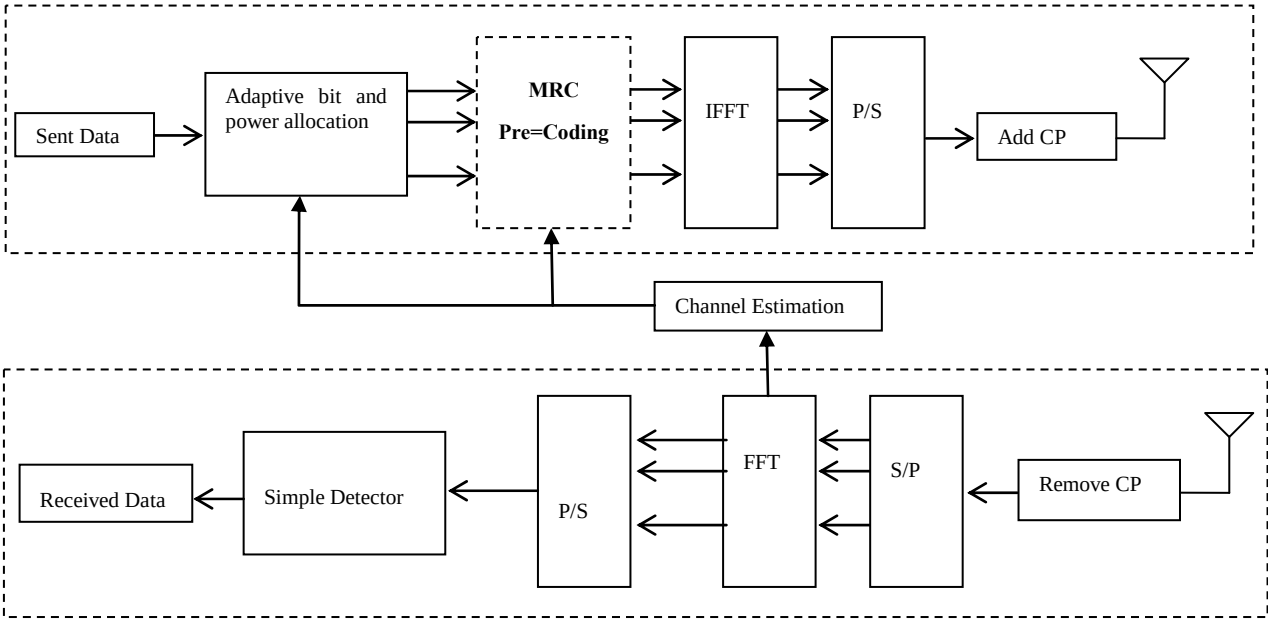

Figure 1. The architecture of the proposed scheme for OFDM system.

Table 2. Pre-LGPA algorithm.

Step	Operation
Input	$b_n^{\text{Pre-UPA}}$, p_k^{excess}, $\gamma_{d,k}^{\text{QAM}} = \gamma_{k_n+1}^{\text{QAM}} - \gamma_{k_n}^{\text{QAM}}$, CNR_n
Initialization	$\forall n \in G_k$ calculate the min. required upgrade power: $p_n^{\text{up}} = \dfrac{\gamma_{d,k}^{\text{QAM}}}{\text{CNR}_n}$ $b_n^{\text{Pre-LGPA}} = b_n^{\text{Pre-UPA}}$ and $p_k^{LO} = p_k^{\text{excess}}$
Recursion	While $p_k^{LO} \geq \min(p_n^{up})$ $j = \arg\min(p_n^{\text{up}})\, n \in G_k$ $p_k^{LO} = p_k^{LO} - p_n^{\text{up}}$ If $k = 0$ $b_{n,k}^{\text{Pre-LGPA}} = \log_2 M_2$, $p_n^{\text{up}} = +\infty$ else $b_{n,k}^{\text{Pre-LGPA}} = \log_2\left(\dfrac{M_{k+1}}{M_k}\right)$, $p_n^{\text{up}} = \dfrac{\left(\gamma_{k_j+1}^{\text{QAM}} - \gamma_{k_j}^{\text{QAM}}\right)}{\text{CNR}_n}$ end end $B_k^{\text{Pre-LGPA}} = \sum_{n \in G_k} b_{n,k}^{\text{Pre-LGPA}}$
Output	$B_k^{\text{Pre-LGPA}}$, p_k^{LO}

each QAM group. This residual power can be exploited by a second stage, whereby it is proposed to move this power upwards starting from the lowest QAM group. This modifies the Pre-LGPA algorithm by considering the left-over power P_0^{LO} of the QAM group G_0 after running the Pre-LGPA algorithm on that group, and assigning this power for redistribution to group G_1. Any left-over power after running Pre-LGPA algorithm on G_1 is then passed further upwards to G_2, and so forth. At the k^{th} algorithmic iteration, the Pre-MuGPA algorithm is working with G_k and tries to allocate the sum of the excess power missed by the Pre-UPA algorithm of that group as well as the left-over power resulting from the application of the Pre-LGPA algorithm to the previous group G_{k-1} *i.e.* $P_k^{\text{excess}} + P_{k-1}^{LO}$. Finally, the left-over power resulting from the QAM group G_{k-1} is added to the excess power of the K^{th} QAM group P_K^{excess} to end up with a final left-over power given by:

$$P_{\text{pre-MuGPA}}^{LO} = P_{K-1}^{LO} + P_K^{\text{excess}} \tag{16}$$

The overall number of the system allocated bits and the used power of this algorithm are, respectively, given by:

$$B_{\text{pre-MuGPA}} = \sum_{k=0}^{K-1} B_k^{\text{pre-MuGPA}} + B_K^{\text{pre-UPA}} \tag{17}$$

$$P_{\text{pre-MuGPA}}^{\text{used}} = P_t - P_{\text{pre-MuGPA}}^{LO} \tag{18}$$

3.4. Pre-Md GPA Algorithm

The residual power P_k^{LO} resulting from the Pre-LGPA algorithm can be exploited by a second algorithm called pre-coded moving down GPA (Pre-MdGPA) algorithm, whereby it is proposed to move the residual power downwards starting from the highest QAM group G_{K-1} to the lowest QAM group G_0, at the k^{th} stage this algorithm applies the Pre-LGPA algorithm for the available power that comprises both the excess power missed by the Pre-UPA algorithm of the previous QAM group G_{k+1} and the left-over power of the previous stage. This will finally result in a left-over power of

$$P_{\text{pre-MdGPA}}^{LO} = P_0^{LO} + P_0^{\text{excess}} \tag{19}$$

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The overall system allocated data bits and the used power of this algorithm are, respectively, given by:

$$B_{\text{pre-MdGPA}} = \sum_{k=0}^{K-1} B_k^{\text{pre-MdGPA}} + B_K^{\text{pre-UPA}} \quad (20)$$

$$P_{\text{pre-MdGPA}}^{\text{used}} = P_t - P_{\text{pre-MdGPA}}^{LO} \quad (21)$$

4. Simulation and Discussions

In this section, computer simulations are carried out to evaluate the performance of the proposed pre-coded bit and power allocation algorithms. For comparison purpose, the non precoded bit and power allocation algorithms are also simulated. Simulation parameters are listed in **Table 3**. Channel coefficients are obtained from complex Gaussian process with zero mean and unit variance through ensemble averages across 1000 channel realizations for various levels of SNRs using QAM modulation schemes, $M_k = 2^k, k = [2 \;\; 4 \;\; 6 \;\; 8]$ with the maximum permissible QAM level of constellation size $M_K = 256$ which is equivalent to 8 bits per data symbol The total average system throughput is studied and shown in **Figures 2** and **3** for the recent (non pre-coded) [12] and proposed (pre-coded) bit and power allocation algorithms with 6 and 12-tabs FIR filters, respectively.

Figure 2 shows that the optimum throughput is achieved by the GPA algorithm in each of the recent and proposed algorithms. However, because of its very large computational complexity, low complexity algorithms are proposed to efficiently use the power budget. These are pre-LGPA, Pre-MuGPA and Pre-MdGPA algorithms. The two proposed MuGPA and MdGPA with and without the MRC pre-coding approach the optimum power allocation GPA algorithm in two distinct SNR regions. MuGPA performs better at low SNRs, while MdGPA performs better at higher SNRs. The proposed precoded algorithms satisfy about 250 bits per symbol throughput enhancement over the non precoded algorithms. **Figure 3** shows that the throughput is improved by about 50 bits per symbol for 12-taps FIR over 6-taps FIR filters due to the multipath diversity of the MRC precoding.

Figure 4 shows the average system throughput versus target BER at SNR = 30 dB. Intuitively, throughput is

Table 3. Simulation parameters.

Parameter	Value
Multipath Channel	6 and 12 tap FIR
Subcarriers Number (N)	64
QAM Level Constellation	[4 16 64 256]
Precoding	MRC
Bit and Power Allocation	UPA, GPA, LGPA, MuGPA, and MdGPA
Channel Estimation	Perfect Channel Estimation

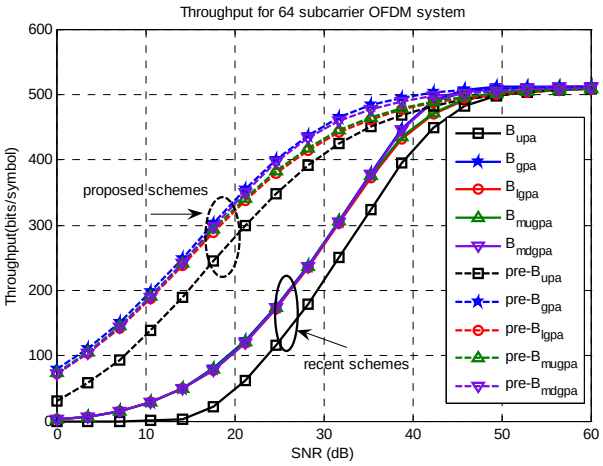

Figure 2. Average system throughput for 64-subcarrier OFDM system with target BER = 10^{-3} and 6-tap FIR.

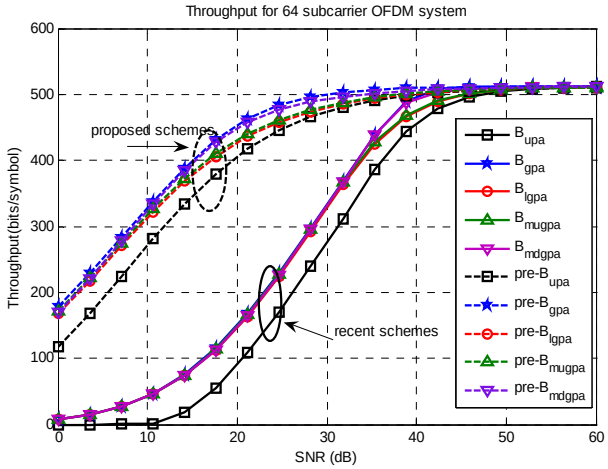

Figure 3. Average system throughput for 64-subcarrier OFDM system with target BER = 10^{-3} and 12-tap FIR.

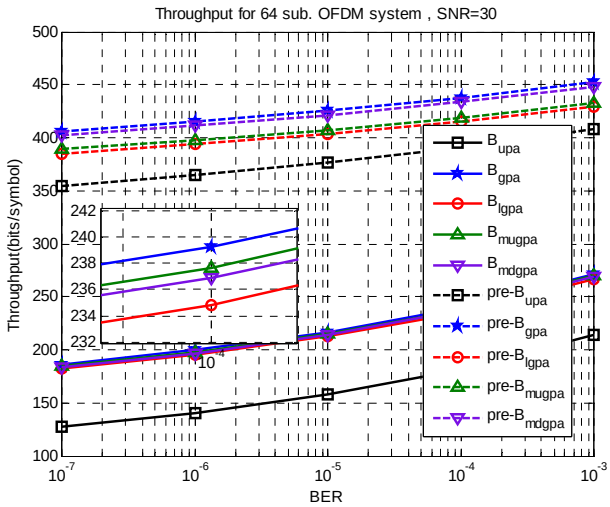

Figure 4. Average system throughput for 64-subcarrier OFDM system with SNR = 30.

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increasing with the increase of target BER. The pre-coded algorithms outperform the non precoded algorithms. The pre-MdGPA achieves about 210 bits/symbol throughput enhancement over pre-MuGPA at target BER = 10^{-7} and 180 bits/symbol at BER = 10^{-3}. This can be attributed to low variation with target BER for pre-coded algorithms compared with the non pre-coded algorithms. Also the pre-MdGPA is better than pre-MuGPA at all target BERs.

Figure 5 shows the used power by all algorithms as a function of the power budget at target BER 10^{-3}. The UPA with and without precoding exhibits the worst performance. The other algorithms are better than UPA in utilizing the transmit power. At low SNRs, all algorithms use approximately all power budget for bit and power allocations with different throughput performance as shown in **Figure 2**. At high SNRs, LGPA and MuGPA algorithms with and without pre-coding approaches the UPA algorithm due to the increase of highest QAM level excess power, which is missed by both of them, and therefore deteriorates their performances. Since **Figure 5** is crowded; it is subdivided into two figures; **Figures 6** and **7** for the recent and the proposed algorithms, respectively.

5. Conclusions

The optimum solution of the discrete bit and power allocation problem is provided by the greedy algorithm, which operates across all subcarriers but it is computationally very expensive. Therefore, in this paper suboptimal low complexity alternatives have been explored in a manner in which the greedy algorithm is applied through subsets of subcarriers, which are grouped according to the QAM levels assigned to them in the uniform power allocation stage. MRC precoding is proposed to enhance the throughput performance of these low complexity

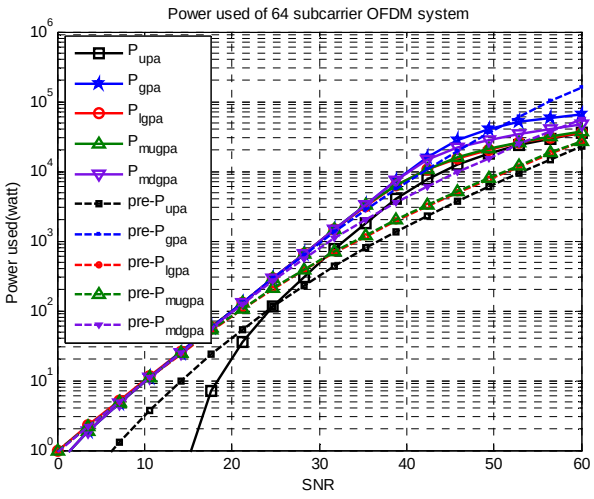

Figure 5. The power used (watt) with target SNR (dB) variation at target BER = 10^{-3} for all algorithms.

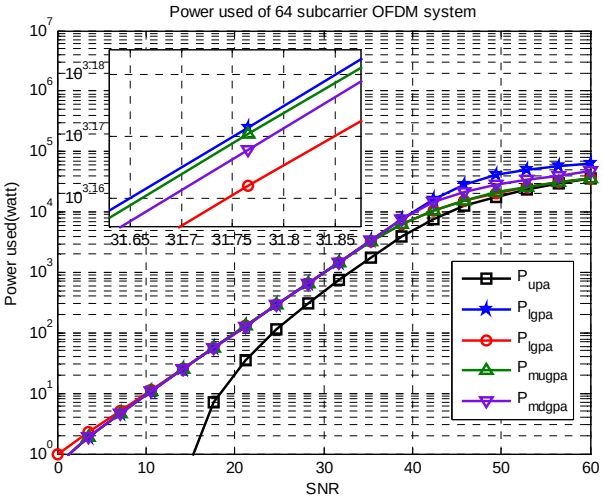

Figure 6. The power used (watt) with target SNR (dB) variation at target BER = 10^{-3} for the recent algorithms.

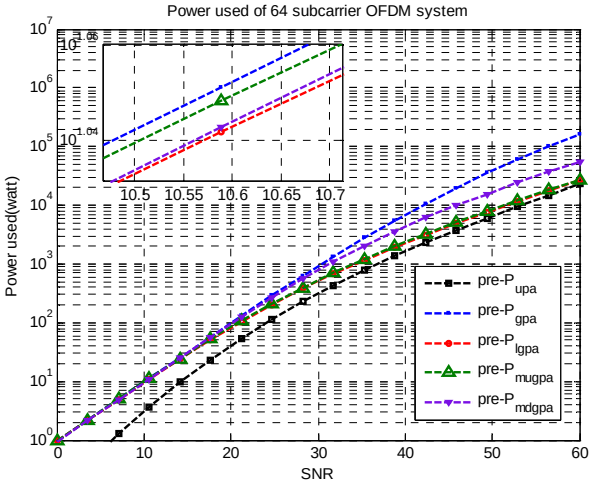

Figure 7. The Power used (watt) with target SNR (dB) variation at target BER = 10^{-3} for the proposed algorithms.

algorithms, the proposed precoded bit and power allocation algorithms outperform the non-pre-equalized algorithms and introduce less variation with target BER. Pre-MuGPA approaches GPA algorithm at low SNRs whereas Pre-MdGPA approaches GPA algorithm and outperforms Pre-MuGPA at high SNRs.

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