NEAR-OPTIMAL JOINT POWER AND RATE ALLOCATION FOR OFDMA BROADCAST CHANNELS

Eduard Calvo * *and Javier R. Fonollosa*

SPCOM Group, Dept. of Signal Theory and Communications, Technical University of Catalonia (UPC)
Jordi Girona 1-3, Campus Nord, Ed. D5, 08034 Barcelona (SPAIN)
Email: {eduard,fono}@gps.tsc.upc.es

ABSTRACT

The problem of maximizing the spectral efficiency of an OFDMA broadcast channel is considered under the practical restriction of single antenna terminals. Given a total transmit power constraint and (possibly) different per-user quality of service (QoS) requirements, a subcarrier assignment and joint power and rate allocation algorithm is proposed to maximize a weighted sum of the users' rates (assuming continuous values for the rates). The proposed solution, which turns out to be a simple rate waterfilling, is very flexible since it can accommodate different scheduling criteria by tuning the users' weights involved in the maximization procedure. The output of the algorithm is quantized so as to restrict the rates to be practical values of squared QAM modulations. For small-sized systems, the comparison of the proposed algorithm with the optimal but impractical brute force search is possible and the results show excellent performance at a much lower complexity load.

***Index Terms*—** Adaptive loading, broadcast channels, orthogonal frequency division multiple-access (OFDMA), MIMO systems

1. INTRODUCTION

Among the different issues that must be considered in the downlink channel of future wireless cellular networks, one challenging problem is the efficient use of the network resources (power, bandwidth, antennas) to achieve higher spectral efficiencies while guaranteeing a target quality of service (QoS), possibly differentiated, to the users of the cell. When channel state information is available at the base station (BS), the resource allocation (RA) policy can be adapted to match the instantaneous network conditions hence achieving higher spectral efficiencies than in the static allocation case.

In the medium to long-term horizon, ongoing standards such as IEEE 802.11 and IEEE 802.16 but also current proposals for 3GPP LTE are likely to provide a solution to that problem within the MIMO framework in conjunction with a multicarrier approach based on OFDM, OFDMA. OFDMA is an appealing modulation and multiple-access technique due to its efficient implementation and capability for dealing with frequency-selective channels. Since the bandwidth is discretized, the RA algorithm reduces to assigning users to subcarriers with some power and rate. In each of the parallel vector channels, MIMO techniques can be used to mitigate multi-user interference and/or boost the achievable rates by means of spatial multiplexing. In a realistic scenario (the current and near-future situation), however, the BS is equipped with more than one antenna, whereas most of the user terminals remain as simple as possible and use one antenna only.

Linear beamformers [1] can be used in this setting, but their performance becomes unacceptable when the channel matrix is ill-conditioned. In this situation, the required transmit power for a given set of QoS constraints becomes extremely large and hence they cannot be satisfied. On the other hand, some of the existing highly efficient non-linear precoders such as vector-perturbation precoding [2] or lattice-reduction methods [3] either require sophisticated receivers or their performance cannot be analytically predicted, or both. Zero-forcing Tomlinson-Harashima precoding (ZF-THP) [4][5], a one-dimensional implementation of the dirty-paper coding concept [6] for the broadcast channel, is a non-linear precoding technique that encompasses the best of both (linear and non-linear) worlds: first, its performance can be explicitly predicted; second, it retains the significant superior performance of non-linear precoding with very simple receivers. This work focuses on the dithered version of ZF-THP, whose main advantage is an accurate prediction of the actual transmit power.

In this paper, we address the problem of maximizing a weighted sum of the users's rates (WSRmax problem), given a total transmit power constraint and (possibly) differentiated QoS requirements, for an OFDMA downlink (broadcast) channel with dithered ZF-THP. The QoS requirements are in the form of a maximum symbol error rate (SER), and can vary for each user. The WSRmax problem is of practical interest from a network operator's point of view since it can be directly applied to the output of any scheduler that computes the weighting factors according to a QoS criterion; examples being the stabilization of the transmission queues or the proportional fair scheduler. Hence, once the users' priorities are given, the RA algorithm tries to get the best out of the current network state.

This paper is organized as follows. In Section 2 we describe the system model and state the WSRmax problem. Section 3 then reviews dithered ZF-THP, the transmit precoding technique chosen to multiplex users in space. In Section 4, an algorithmic solution to the WSRmax problem is proposed. The performance of the proposed algorithm is compared to a brute force search in Section 5. Finally, Section 6 concludes the paper.

2. SYSTEM MODEL AND PROBLEM STATEMENT

We consider a BS equipped with n_T antennas and total transmit power P_T serving K users at a given time slot. At the BS, the bandwidth is partitioned into N_c subcarriers via OFDM. We do not

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restrict K to any value, and, in general, it will be greater than n_T. However, for the sake of facilitating the signal detection at the user terminals, only a maximum of $L = \min\{n_T, K\}$ users will be assigned to the same subcarrier. Variables in subindexes will index users, while variables inside brackets will index subcarriers. Let $\mathcal{U}[n] = \{k_1, \ldots, k_L\}$, be the *ordered* set of users to which the BS will transmit on subcarrier n. After OFDM modulation and demodulation, the signal model for that subcarrier is

$$\mathbf{y}[n] = \mathbf{H}[n]\mathbf{x}[n] + \mathbf{w}[n], \tag{1}$$

where $\mathbf{y}[n] = [y_{k_1}[n] \ldots y_{k_L}[n]]^T \in \mathbb{C}^{L\times 1}$ is the received signal at the mobile terminals, $\mathbf{H}[n] = [\mathbf{h}_{k_1}[n] \ldots \mathbf{h}_{k_L}[n]]^T \in \mathbb{C}^{L\times n_T}$ is the channel matrix, $\mathbf{h}_{k_i}[n] \in \mathbb{C}^{n_T\times 1}$ is the channel vector of the i-th user allocated in subcarrier n, $\mathbf{x}[n] \in \mathbb{C}^{n_T\times 1}$ is the transmitted vector, and $\mathbf{w}[n] \in \mathbb{C}^{L\times 1}$ is the noise vector, with uncorrelated entries drawn $\mathcal{CN}(0, \sigma_{k_i}^2)$, $1 \le i \le L$. The vector $\mathbf{x}[n]$ bears the information symbols $\{s_{k_1}[n], s_{k_2}[n], \ldots, s_{k_L}[n]\}$, each one uniformly drawn from a square $M_{k_i}[n]$-QAM constellation thus yielding a rate of $R_{k_i}[n] = \log_2(M_{k_i}[n])$ [bit/ ch.use] for user k_i at subcarrier n. The transmission of $s_{k_i}[n]$ consumes a power $p_{k_i}[n]$, such that $E\{\|\mathbf{x}[n]\|^2\} = \sum_{i=1}^{L} p_{k_i}[n]$.

If $k \in \mathcal{U}[n]$, the k-th user terminal estimates the symbol $s_k[n]$ from its output $y_k[n]$, incurring in a SER denoted by $\mathrm{SER}_k[n]$ which is decreasing in $p_k[n]$ and increasing in $R_k[n]$, and whose expression depends on the precoding technique. We denote by SER_k^0 the target QoS for user k. Since the SER of non-linear precoders depends on the user encoding order within the subcarrier, we considered *ordered* sets to describe the subcarrier assignment.

The WSRmax problem is the maximization of a weighted sum of the users' rates satisfying the QoS and transmit power constraints, for some non-negative weights $\{\mu_k\}_{k=1}^K$ given by the scheduler.

$$\begin{aligned}
\underset{\{p_k[n], R_k[n], \mathcal{U}[n]\}}{\text{maximize}} \quad & \sum_{k=1}^{K} \mu_k \sum_{n:k\in\mathcal{U}[n]} R_k[n] \\
\text{subject to} \quad & \mathrm{SER}_k[n] \le \mathrm{SER}_k^0,\ \forall n : k \in \mathcal{U}[n] \\
& p_k[n], 0 \le R_k[n] \le R_{max},\ \forall n : k \in \mathcal{U}[n] \\
& \sum_{k=1}^{K} \sum_{n:k\in\mathcal{U}_k[n]} p_k[n] \le P_T
\end{aligned} \tag{2}$$

Practical systems employ square QAM modulations of rate $R \in \mathcal{R} = \{0, 2, 4, \ldots, R_{max}\}$ with R_{max} an even integer ($R = 0$ meaning no transmission. We denote by $R_k = \sum_{n:k\in\mathcal{U}[n]} R_k[n]$ the total rate of user k. The maximization in (2) is with respect to the power allocation, the bit loading, and the *ordered* subcarrier assignment. Out of these, obtaining the optimal subcarrier assignment is a combinatorial problem whose solution follows from a prohibitive complete search among all the possible assignments. Instead, in Section 4 we propose a heuristic but tractable method for building the sets $\{\mathcal{U}[n]\}_{n=1}^{N_c}$ whose performance is analyzed in Section 5.

3. DITHERED ZF-THP

In this Section we derive the expression of $\mathrm{SER}_k[n]$ as a function of $p_k[n]$ and $R_k[n]$ of dithered ZF-THP. Without loss of generality, we focus on one specific subcarrier for which $\mathcal{U}[n] = \{1, 2, \ldots, L\}$. The subcarrier index will be dropped for the sake of clarity.

Consider the transmission of $\{s_1, \ldots, s_L\}$ through the channel (1). After QR decomposition of the channel matrix, $\mathbf{H} = \mathbf{GQ}$ with $\mathbf{G}$ lower triangular and $\mathbf{Q}$ unitary, we linearly precode the vector $\mathbf{x}$ as $\mathbf{x} = \mathbf{Q}^H\mathbf{x}'$. Hence, the per-user input-output expressions are

$$y_k = g_{kk}x'_k + \sum_{j<k} g_{kj}x'_j + w_k, \tag{3}$$

where the notation $g_{ij} = [\mathbf{G}]_{i,j}$ has been used. In dithered ZF-THP the components x'_k are chosen according to the expression

$$x'_k = (s_k - \alpha_k \sum_{j<k} \frac{g_{kj}}{g_{kk}} x'_j - u_k) \bmod \rho_k,\ 1 \le k \le L, \tag{4}$$

where $x \bmod \rho_k$ is the unique representation of each component of x inside the fundamental interval $[-\rho_k/2, \rho_k/2)$. The symbol s_k belongs to an M_k-QAM square constellation with symbol spacing $2d_k = \sqrt{3p_k/2M_k}$ and $\rho_k = 2\sqrt{M_k}d_k$ in order to fit the entire constellation inside. The dither [6] u_k is a random variable, a priori known by the BS and the k-th user terminal, drawn uniform inside the fundamental region $[-\rho_k/2, \rho_k/2) + j[-\rho_k/2, \rho_k/2)$. It provides x'_k with a uniform statistic regardless of the values of the precanceled symbols and, hence, its power is accurately $E\{|x'_k|^2\} = p_k$. Existing works in the literature [4][5] not considering dithering rely on the fact that x'_k tends asymptotically (as k' goes large) to a uniform distribution, and that the actual power $E\{|x'_k|^2\}$ without dither is bounded within two bounds that meet when M_k is large [7]. However, practical systems with sharp transmit power constraints cannot rely on asymptotical results and hence dithering is necessary in order to predict the actual power budget consumption.

The receiver, which is assumed to have full channel knowledge, computes the symbol estimate $\hat{s}_k = (\alpha_k y_k/g_{kk} + u_k) \bmod \rho_k$, which can be shown to be equal in distribution [8, Lemma 1] to

$$\hat{s}_k = (s_k + z_k) \bmod \rho_k, \tag{5}$$

where z_k equals $(1 - \alpha_k)u_k + \alpha_k w_k/g_{kk}$ in distribution. Then, the parameter α_k can be optimized to minimize the power $\sigma_{z_k}^2 = E\{|z_k|^2\}$ of the equivalent noise. Its optimal value is $\alpha_k^\star = p_k(p_k + \sigma_k^2/|g_{kk}|^2)^{-1}$ which yields an equivalent noise power of

$$\sigma_{z_k}^2 = \frac{p_k}{p_k + \sigma_k^2/|g_{kk}|^2}\sigma_k^2/|g_{kk}|^2 < \sigma_k^2/|g_{kk}|^2. \tag{6}$$

After a worst-case Gaussian approximation of z_k, the SER achieved by dithered ZF-THP is

$$\begin{aligned}
\mathrm{SER}_k &= 1 - (1 - 2\mathcal{Q}(\sqrt{2}d_k/\sigma_{z_k}))^2 \approx 4\mathcal{Q}(\sqrt{2}d_k/\sigma_{z_k}) \\
&= 4\mathcal{Q}\left(\sqrt{3(c_k p_k + 1)2^{-R_k}}\right),
\end{aligned} \tag{7}$$

where $\mathcal{Q}(x) \triangleq \int_x^{+\infty} \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$ is the Q-function, the equivalent squared channel is $c_k = |g_{kk}|^2/\sigma_k^2$, and $M_k = 2^{R_k}$ has been used. Since c_k depends on g_{kk} via QR decomposition of $\mathbf{H}$, which is sensitive to the ordering of its rows, the subcarrier assignment of Section 4 will have to deal not only with the mapping of users to subcarriers but also with the ordering of users within a subcarrier.

4. PROPOSED RESOURCE ALLOCATION ALGORITHM

The proposed RA algorithm is structured in three stages. First, the heuristic subcarrier assignment (construction of the sets $\mathcal{U}[n]$); second, the solution of the WSRmax problem with respect to $\{p_k[n]\}$ and $\{R_k[n]\}$ assuming that $\{R_k[n]\}$ are continuous variables; third, the quantization of the RA so as to constrain $\{R_k[n]\}$ to take on even integer values yielding proper square QAM constellations.

4.1. Subcarrier assignment algorithm

In order to take advantage of the multiuser gain when $K \gg n_T$, we propose to select the users of subcarrier n based on the channel energies $E_k[n] = \|\mathbf{h}_k[n]\|^2$ and user priorities. This way, users with small priorities will not be (on average) assigned more subcarriers than others with larger μ's and hence the power will be efficiently used. The description of the algorithm is as follows.

Algorithm *Subcarrier assignment*
1. Compute the channel energies $\{E_k[n]\}, \forall k, n$.
2. **for** $n \leftarrow 1$ **to** N_c
3. Select the L users with highest product $\mu_k E_k[n]$.
4. Form the ordered set $\mathcal{U}[n] = \{k_1, \ldots, k_L\}$ such that $E_{k_1}[n] \geq E_{k_2}[n] \geq \ldots \geq E_{k_L}[n]$.
5. Form the channel matrix $\mathbf{H}[n]$ with proper row ordering, do QR decomposition and compute $c_k[n]$, $k \in \mathcal{U}[n]$.

Usually (if $\mathbf{H}[n]$ is i.i.d. complex Gaussian and the user ordering is random) $E\{|g_{kk}[n]|^2\}$ is highly decreasing in k [9]: users allocated first experience (on average) much better channel conditions. Since we impose fairness in step 3 by taking into account the user priorities to perform subcarrier-wise user selection, in step 4 we use an ordering based on decreasing energies so that those users with larger energies can benefit from better channel conditions.

4.2. Continuous power and rate allocation

When the SER constraints in (2) are rephrased using expression (7), we obtain after some algebra the following set of simpler equations

$$\log_2(c_k[n]p_k[n]+1) - R_k[n] - \gamma(\mathrm{SER}_k^0) \geq 0, \ \forall n : k \in \mathcal{U}[n],$$

where $\gamma(\mathrm{SER}_k^0) \triangleq \log_2\left(\left(\mathcal{Q}^{-1}(\mathrm{SER}_k^0/4)\right)^2/3\right)$ is a constant, and $\mathcal{Q}^{-1}$ is the inverse Q-function. Then, the WSRmax problem becomes

$$\underset{\{p_k[n], R_k[n]\}}{\text{maximize}} \sum_{k=1}^{K} \mu_k \sum_{n:k\in\mathcal{U}[n]} R_k[n] \tag{8}$$

$$\text{subject to} \quad \log_2(c_k[n]p_k[n]+1) - R_k[n] - \gamma(\mathrm{SER}_k^0) \geq 0 \tag{9}$$

$$p_k[n] \geq 0, \ 0 \leq R_k[n] \leq R_{max} \tag{10}$$

$$\sum_{k=1}^{K} \sum_{n:k\in\mathcal{U}[n]} p_k[n] \leq P_T \tag{11}$$

The constraints (9)(10) apply for $n : k \in \mathcal{U}[n]$ (otherwise $p_k[n] = R_k[n] = 0$). The upper bound in (10) accounts for the maximum modulation order allowed in the system. On the other hand, (9) only has to be considered in case $R_k[n] > 0$, otherwise setting $p_k[n] = 0$. If we define the sets $\mathcal{S}_k$ of cardinality s_k, $1 \leq k \leq K$, as

$$\mathcal{S}_k = \{n : k \in \mathcal{U}[n] \ , \ R_k[n] > 0\}, \ s_k = |\mathcal{S}_k|, \tag{12}$$

optimization over the sets $\{\mathcal{S}_k\}$ into (8) is also necessary in order not to allocate any power in case of zero rate. Again, to avoid combinatoric search we resort to a heuristic construction of $\{\mathcal{S}_k\}$ embedded into the algorithm. For some fixed $\{\mathcal{S}_k\}$, the problem at hand is convex. By computing the KKT conditions of (8) it can be verified that the *optimal* rate and power of user k at some subcarrier $n \in \mathcal{S}_k$ has the clipped rate waterfilling structure (see [10] for the details)

$$R_k[n] = \min\left\{\log_2\left(\frac{\mu_k}{\theta} c_k[n]\right) - \gamma(\mathrm{SER}_k^0), R_{max}\right\} \tag{13}$$

$$p_k[n] = (2^{R_k[n]+\gamma(\mathrm{SER}_k^0)} - 1)/c_k[n], \tag{14}$$

where θ has to be chosen to satisfy the power constraint (11) with equality. If we define $\mathcal{C}_k$ as the set of clipped subcarriers of user k,

$$\mathcal{C}_k = \{n \in \mathcal{S}_k \ : \ R_k[n] = R_{max}\} \subseteq \mathcal{S}_k, \ c_k = |\mathcal{C}_k|, \tag{15}$$

the parameter θ can be explicitly computed as

$$\theta = \frac{\sum_{k=1}^{K} \mu_k (s_k - c_k)}{P_T + \sum_{k=1}^{K} \left(\sum_{n\in\mathcal{S}_k} c_k^{-1}[n] - 2^{R_{max}+\gamma(\mathrm{SER}_k^0)} \sum_{n\in\mathcal{C}_k} c_k^{-1}[n] \right)}, \tag{16}$$

and the allocation algorithm is as follows.

Algorithm *Joint power and rate allocation*
1. Set $\mathcal{S}_k = \{n : k \in \mathcal{U}[n]\}, \mathcal{C}_k = \emptyset$, $s_k = |\mathcal{S}_k|$, $c_k = 0 \ \forall k$.
2. Compute the waterlevel θ (16).
3. **repeat**
4. Compute the rate allocation (13) for $n \in \mathcal{S}_k \setminus \mathcal{C}_k, \forall k$.
5. **for** all (k, n) such that $R_k[n]$ equals R_{max}
6. Update $\mathcal{C}_k = \mathcal{C}_k \cup n$, $c_k = c_k + 1$ and go to 4.
7. **if** $R_k[n] < 0$ for some $n \in \mathcal{S}_k$, $1 \leq k \leq K$
8. Set $(k', n') = \arg\min_{k,n} R_k[n]$.
9. Update $\mathcal{S}_{k'} = \mathcal{S}_{k'} \setminus n'$, $s_{k'} = s_{k'} - 1$.
10. Set $R_{k'}[n'] = p_{k'}[n'] = 0$ and $\mathcal{C}_k = \emptyset$, $c_k = 0 \ \forall k$.
11. **until** $R_k[n] > 0 \ \forall n \in \mathcal{S}_k$, $1 \leq k \leq K$.
12. Compute the power allocation (14) $\forall n \in \mathcal{S}_k, \forall k$.

This algorithm ends up with an *optimal* rate and power allocation for the final $\{\mathcal{S}_k\}$, but we cannot guarantee that these sets are the optimal ones.

4.3. Quantization of the resource allocation

Given a set $\mathcal{R}$ of feasible values for the rates, denote by $R_k^q[n] = q(R_k[n], \mathcal{R})$ the projection of $R_k[n]$ onto $\mathcal{R}$ by the nearest neighbor criterion (a regular slicer) and by $p_k^q[n]$ the updated power allocation (according to (14)) but set $p_k^q[n] = 0$ if $R_k^q[n] = 0$). Denote by $P = \sum_{k=1}^{K} \sum_{n:k\in\mathcal{U}[n]} p_k^q[n]$ the total transmit power of the quantized rate allocation. For a given value of rate $R \in \mathcal{R}$ of the k-th user at the n-th subcarrier, define $\Delta_k^+[n]$ as the extra power required to increase R in 2 bits per symbol (calculated using (14) and set to $+\infty$ in case $R = R_{max}$), and define $\Delta_k^-[n]$ as the extra power obtained when R is decreased in 2 bits per symbol (set to 0 in case $R = 0$).

Algorithm *Rate and power quantization*
1. **if** $P < P_T$
2. **repeat** $(k', n') = \arg \min_{k,n \ : \ P+\Delta_k^+[n] \leq P_T} \Delta_k^+[n]/\mu_k$
3. Set $R_{k'}^q[n'] = R_{k'}^q[n'] + 2$, $P = P + \Delta_{k'}^+[n']$, and update $(p_{k'}^q[n'], \Delta_{k'}^+[n'], \Delta_{k'}^-[n'])$.
4. **until** $P + \Delta_k[n] > P_T \ \forall n, k$.
5. **else**
6. **repeat** $(k', n') = \arg \max_{k,n \ : \ \Delta_k^-[n]>0} \Delta_k^-[n]/\mu_k$
7. Set $R_{k'}^q[n'] = R_{k'}^q[n'] - 2$, $P = P - \Delta_{k'}^-[n']$, and update $(p_{k'}^q[n'], \Delta_{k'}^+[n'], \Delta_{k'}^-[n'])$.
8. **until** $P \leq P_T$

If there is spare power after quantization, the rates of users with large priorities or small power demands to increase their rate are increased. If we need to cut down power instead, we decrease the rates of those users with lowest priorities or very large power returns if their rate is reduced.

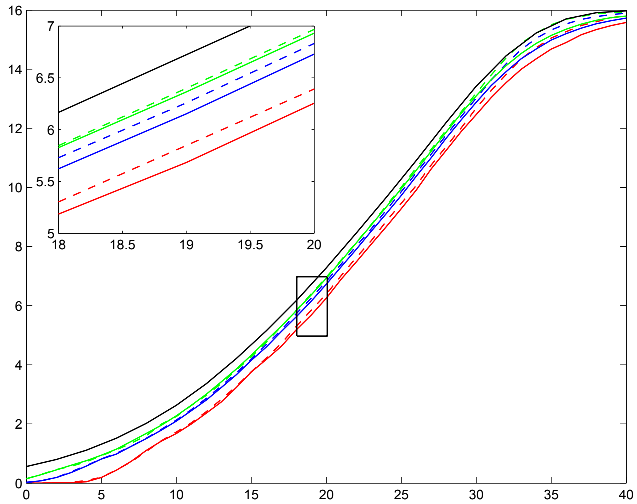

Fig. 1. Total spectral efficiency C [bit/s/Hz] as a function of P_T/N_c [dB] for $K = 2$ users, and $N_c = 1$ (red), 2 (blue), 3 (green), and 63 (black) subcarriers. Dashed lines represent exhaustive search, while solid lines represent the proposed algorithm.

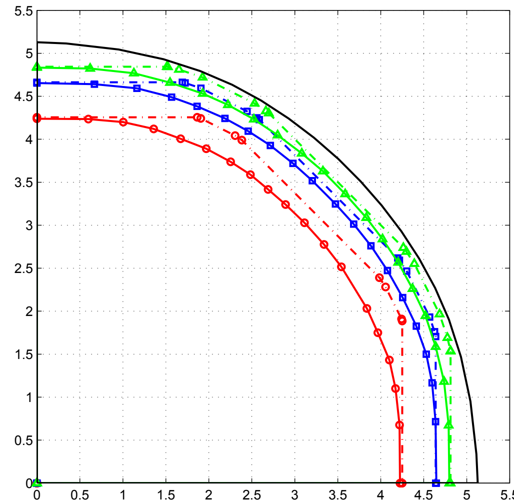

Fig. 2. Achievable spectral efficiency region [bit/s/Hz] for $P_T/N_c =$ 20 [dB], $K = 2$ users, and $N_c = 1$ (circles), 2 (squares), 3 (triangles), and 63 (no marker) subcarriers. Dash-dot lines represent exhaustive search, while solid lines represent the proposed algorithm.

5. PERFORMANCE EVALUATION

The performance of the proposed RA algorithm has been evaluated in terms of (1) total spectral efficiency $\mathsf{C} = (\sum_k R_k)/N_c$ (where $\{R_k\}$ are the solution of the WSRmax problem with $\mu_k = 1/K$) in Figure 1; and (2) achievable spectral efficiency region, the achieved points $(R_1, R_2, \ldots, R_K)/N_c$ for different user priorities, in Figure 2. A fair benchmarking of the proposed algorithm has been provided through the comparison with a brute force algorithm selecting the subcarrier assignment, rate and power allocation maximizing the WSRmax objective value after an exhaustive search.

For the simulations, 10^3 Montecarlo runs were averaged. In each of them, the channels were i.i.d. randomly generated according to a zero-mean circularly symmetric complex Gaussian distribution of unit power, and $n_T = 2$. The noise powers $\sigma_k^2 = 1$, and the SER constraints $\mathrm{SER}_k^0 = 10^{-3}\ \forall k$. The set of feasible rate values was $\mathcal{R} = \{0, 2, 4, 6, 8\}$ [bit/symbol].

With respect to the C curve showed in Figure 1, the proposed algorithm and the brute force benchmark behave indistinguishably for moderate to large values of P_T; for large values of P_T the difference is less than 0.25 dB at $P_T/N_c = 30$ dB. On the other hand, we can observe in Figure 2 that the difference of the spectral efficiency region achieved by the proposed algorithm and the exhaustive search is negligible when the priorities are highly unbalanced. When the priorities are similar, the relative difference between both regions tends to decrease as N_c increases.

6. CONCLUSIONS

We have proposed an algorithm for weighted sum rate maximization based on subcarrier assignment, and power and rate loading across subcarriers for an OFDMA downlink channel with dithered ZF-THP non-linear precoders and single-antenna users. The algorithm, whose structure is based on a clipped rate waterfilling solution, is able to perform close to the optimal exhaustive search allocation at a complexity load several orders of magnitude below.

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