A Fair Power Allocation for Non-Orthogonal Multiple Access in the Power Domain[☆]

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A R T I C L E   I N F O.

Abstract

This paper presents an investigation on the performance of the Non-Orthogonal Multiple Access (NOMA) in the power domain scheme. A Power Allocation (PA) method is proposed from NOMA throughput expression analysis. This method aims to provide fair opportunities for users to improve their performance. Thus, NOMA users can achieve rates higher than, or equal to, the rates obtained with the conventional Orthogonal Multiple Access (OMA) in the frequency domain schemes. The proposed method is evaluated and compared with others PA techniques by computer system level simulations. The results obtained indicate that the proposed method increases the average cell spectral efficiency and maintains a good fairness level with regard to the resource allocation among the users within a cell.

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1 Introduction

The scenario for mobile communication services has changed rapidly in the past years. The gradual arrival of Internet of Things (IoT) has increased the number of devices connected to the worldwide network. In addition, several new services are now offered by virtual platforms, and the existing services require increased data transmission. Consequently, the demand for mobile access to the Internet has grown significantly [1].

To address this demand, new technologies are being proposed to increase system capacity, support massive connections, and deliver high data rates [2], as imposed by the Fifth Generation (5G) requirements. One of the proposals is the Non-Orthogonal Multiple Access (NOMA) technique in the power domain. With NOMA it is possible for multiple users to use the same frequency and time features by exploiting power multiplexing as an additional domain.

The NOMA can provide a real capacity increase, with few changes, in existing systems because it does

not require allocation of new bands of the spectrum or any disruptive changes in existing systems. In addition, the signal processing for NOMA can be implemented in software, which implies changes of small impact and low cost in the user device.

The use of NOMA in the power domain on downlink system, permits the Base Station (BS) to send overlapping messages for several users, taking advantage of the difference in channel conditions experienced by users in the cell, to increase the channel capacity region. On the receiver side, User Equipment (UE) apply Successive Interference Cancellation (SIC) to decode the message [3]. The mobile communication downlink system that uses NOMA as a multiple access technique corresponds to the broadcast channel and the theoretical model from information theory [4].

The remainder of the paper is organized as follows. A brief summary of related work is presented in section 2. Section 3 presents the considered system model, and describes the main concepts of the NOMA technique. Section 4 shows the gain provided by the NOMA technique compared to the OMA scheme. Section 5 presents the proposed fairness criterion and the calculation of the power allocation coefficient. The Simulation scenarios and performance metrics are described in section 6. Section 7 discusses the obtained results, and section 8 summarizes the final considerations and presents future research proposals.

2 Related Work

Previous work has shown that NOMA has a potential to increase the user throughput in multiple access [5, 6]. The fair distribution of resources among NOMA users was addressed in [7]. A method is proposed in [8, 9], to promote a proportional fairness-based of User Pairing and Power Allocation (UPPA) for NOMA. In [10] the power and bandwidth allocation are jointly optimized in order to maximize the system energy efficiency (EE) under transmit power and users rate constraints. The work [11] presents an evaluation of NOMA considering the Power Allocation (PA) method with fixed coefficient. This paper proposes a simple and fair method PA method for NOMA users, whose performance is evaluated under different scenarios by computational simulations.

3 System Model

The conducted research considered a cellular system with L cells and J users connected by cell. Each cell operates with a channel bandwidth W subdivided into M equals sub-bands of bandwidth $W_{SB} = W/M$ on downlink. The total transmission power per cell is P_t and is equally distributed among the sub-bands, and K users are allocated per sub-band.

The SINR γ_k of the user U_k where $k \in \{1, 2, \ldots, K\}$ is allocated exclusively in the sub-band S_m where $m \in \{1, 2, \ldots, M\}$)of the cell C_l ($l \in \{1, 2, \ldots, L\}$) is given by

$$\gamma_{k,l} = \frac{P_{R,l,k}}{I_{l,k} + N_0} \tag{1}$$

in which $P_{R,l,k}$ is the power received by user U_k connected to cell C_l, considering large-scale loss and small-scale fading effects. The power of the Additive White Gaussian Noise (AWGN) over the sub-band is N_0 and the power interference received from others BS that are transmitting on the same reuse sub-band frequency is $I_{l,k} = \sum_{i=1,i\neq l}^{C} P_{R,i,k}$.

For simplicity, without loss of generality, the cell index l can be omitted. Ordering the users in a decreasing order of channel gain ($\gamma_k \geq \gamma_{k+1}$) it is possible to obtain the SINR for a NOMA user U_k, as a function of γ_k and the Power Allocation (PA) coefficient a_k using the following expression,

$$\phi_k = \frac{a_k \gamma_k}{\gamma_k \sum_{i=0}^{k-1} a_i + 1} \tag{2}$$

in which $\sum_{i=1}^{K} a_i = 1$, therefore the PA coefficient is given by

$$a_k = 1 - \sum_{i=1,i\neq k}^{K} a_i \tag{3}$$

Thus, the throughput achievable by a NOMA user U_k on a sub-band of bandwidth W_{SB} is

$$R_{N,k} \leq W_{SB} \log_2(1 + \phi_k) \tag{4}$$

In the same way that the SINR was defined for NOMA users by equation 2, the SINR for the same users can be defined for Orthogonal Multiple Access (OMA) in the frequency domain.

Assuming that the bandwidth and transmission power are equally divided among the K users, the power received by the k-th user allocated in the l-th cell is $P_{R,l,k}/K$. The power of interference plus noise is $\beta_k(I_{l,k} + N_0)$. From the assumption that each user in OMA uses the same proportion of the sub-band, the band allocation coefficient can be defined as $\beta_k = \beta = 1/K$. Therefore, omitting the cell index l, the SINR for the a OMA user U_k is

$$\theta_k = \frac{P_{R,k}/K}{\beta(I_k + N_0)} = \gamma_k \tag{5}$$

Thus, the throughput achievable by a OMA user U_k is

$$R_{O,k} \leq \beta W_{SB} \log_2(1 + \theta_k) \tag{6}$$

Without loss of generality, a cell with two users ($K = 2$) allocated by sub-band is assumed. The users

are indexed in decreasing order of channel gain ($\gamma_1 \geq \gamma_2$) and $\gamma_2 > 0$. The resource allocation coefficients for NOMA and OMA are, respectively, $\mathbf{a} = [\alpha, (1-\alpha)]$ and $\beta = 1/2$. In this way, the achievable rates in NOMA are:

$$R_{N,1} \leq W_{SB} \log_2(1 + \alpha\gamma_1) \tag{7}$$

$$R_{N,2} \leq W_{SB} \log_2\left(1 + \frac{(1-\alpha)\gamma_2}{\alpha\gamma_2 + 1}\right) \tag{8}$$

and in OMA:

$$R_{O,k} \leq \frac{W_{SB}}{2} \log_2(1 + \gamma_k) \quad k \in \{1, 2\} \tag{9}$$

The behavior of (7) to (9) can be evaluated from their arguments. In order to simplify the analysis, the following functions are defined:

$$f_{N,1}(\alpha, \gamma_1) \triangleq 1 + \alpha\gamma_1 \tag{10}$$

$$f_{N,2}(\alpha, \gamma_2) \triangleq \frac{(1 + \gamma_2)}{(1 + \alpha\gamma_2)} \tag{11}$$

$$f_{O,k}(\gamma_k) \triangleq \sqrt{1 + \gamma_k} \quad k \in \{1, 2\} \tag{12}$$

The previous expressions show that an increase in the PA coefficient α causes an increase of the rate achievable by user U_1 (the user with higher SINR), and also reduces the rate achievable by the user U_2.

4 NOMA Gain

The use of NOMA to multiplex users in the same subband, permits to obtain an improved combination of the individual communication rates when compared to OMA. It is possible to show that there is always a user pair and a power allocation configuration in NOMA which provides a system performance that is better than or equal to the system performance in OMA.

In order to ensure the fairness on resource allocation among the users, the power allocation coefficient α must be set so that both paired users in NOMA obtain simultaneous performance gains when compared to OMA. This idea is formally introduced with the following property.

Property 4.1 ($R_N \geq R_O$). For all pair of users (U_1, U_2) in multiple access with $\gamma_1 \geq \gamma_2 > 0$ there exists $\alpha \in \mathbb{R}$, such that, $0 \leq \alpha \leq \frac{1}{2}$, which simultaneously satisfies the following inequalities

$$R_{N,1} \geq R_{O,1} \quad \text{and} \quad R_{N,2} \geq R_{O,2} \tag{13}$$

Proof. From (10) to (13), for the proposition to be true, the following relations must exist,

$$1 + \alpha\gamma_1 \geq \sqrt{1 + \gamma_1} \quad \text{and} \quad \frac{1 + \gamma_2}{1 + \alpha\gamma_2} \geq \sqrt{1 + \gamma_2} \tag{14}$$

so that

$$\frac{\sqrt{1 + \gamma_1} - 1}{\gamma_1} \leq \alpha \leq \frac{\sqrt{1 + \gamma_2} - 1}{\gamma_2} \tag{15}$$

Therefore, there must be a pair (γ_1, γ_2), such that,

$$\frac{\sqrt{1 + \gamma_1} - 1}{\gamma_1} \leq \frac{\sqrt{1 + \gamma_2} - 1}{\gamma_2} \tag{16}$$

Starting from the initial considerations, one has

$$\begin{gathered} \gamma_2 \leq \gamma_1 \\ \sqrt{1 + \gamma_2} + 1 \leq \sqrt{1 + \gamma_1} + 1 \end{gathered} \tag{17}$$

and

$$\begin{gathered} \gamma_1 > 0 \\ \sqrt{1 + \gamma_1} - 1 > 0 \end{gathered} \tag{18}$$

Thus, it is possible to multiply both sides of (17) by the left side of the (18), without no signal change, to obtain

$$(\sqrt{1 + \gamma_1} - 1)(\sqrt{1 + \gamma_2} + 1) \leq \tag{19}$$
$$(\sqrt{1 + \gamma_1} - 1)(\sqrt{1 + \gamma_1} + 1)$$
$$(\sqrt{1 + \gamma_1} - 1)(\sqrt{1 + \gamma_2} + 1) \leq \gamma_1$$
$$\frac{(\sqrt{1 + \gamma_1} - 1)(\sqrt{1 + \gamma_2} + 1)}{\gamma_2} \leq \frac{\gamma_1}{\gamma_2}$$
$$\frac{(\sqrt{1 + \gamma_1} - 1)(\sqrt{1 + \gamma_2} + 1)}{(\sqrt{1 + \gamma_2} - 1)(\sqrt{1 + \gamma_2} + 1)} \leq \frac{\gamma_1}{\gamma_2}$$

and finally,

$$\frac{\sqrt{1 + \gamma_1} - 1}{\gamma_1} \leq \frac{\sqrt{1 + \gamma_2} - 1}{\gamma_2} \tag{20}$$

Therefore, there is at least one $\alpha \in \mathbb{R}$ that satisfies (15). The bounds of the interval to which α belongs can be obtained by calculating the upper limit and lower limit of both sides of (15) [12]:

$$\lim_{\gamma_1 \to \infty} \frac{\sqrt{1 + \gamma_1} - 1}{\gamma_1} = \lim_{\gamma_1 \to \infty} \frac{1}{\sqrt{1 + \gamma_1} + 1} = 0 \tag{21}$$

$$\lim_{\gamma_2 \to 0} \frac{\sqrt{1 + \gamma_2} - 1}{\gamma_2} = \lim_{\gamma_2 \to 0} \frac{1}{\sqrt{1 + \gamma_2} + 1} = \frac{1}{2} \tag{22}$$

This concludes that $\alpha \in \mathbb{R}$ is within the interval $[0, \frac{1}{2}]$, and satisfies the mentioned proposition. □

The previous property shows that for the paired users to experience performance gains in NOMA, a fraction equal to or larger than half of the total transmission power per sub-band is required to be allocated to the message that is intended for the user with the lowest SINR (γ_2). Figure 1 highlights the region in which the values of α can provide gain for NOMA users.
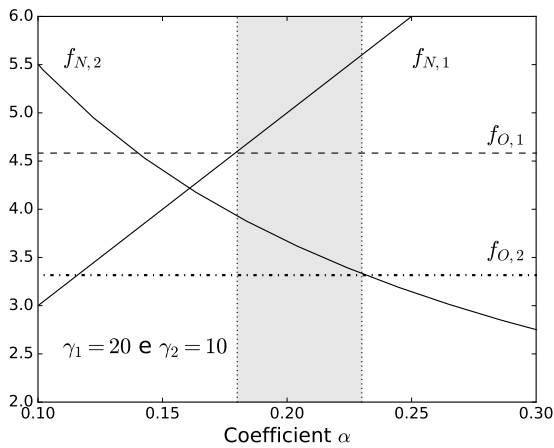
Figure 1. NOMA gain region for $\gamma_1 = 20$ and $\gamma_2 = 10$

5 Fair Power Allocation

The power allocation coefficient α should be chosen to maximize the spectral efficiency and the fairness among users. However, it is not possible to guarantee that the paired users reach the same data rate, since each user experiences different propagation conditions. Thus, if the PA coefficient α is chosen to force the same rate for both users of a NOMA pair, the user with a high SINR would be limited to the rates provided by the lower SINR of the other user. This would cause a waste of spectral resources that could be best enjoyed by the user with higher channel gain.

Given that the power allocation coefficient directly affects the SINR levels of each user, a fairness criterion based on the fraction of the total SINR that each user can achieve is proposed. The total SINR γ_k of a user U_k is obtained when this user is allocated exclusively in the sub-band, and is defined by (1). The fraction of γ_k that U_k gets after being paired in NOMA, is defined as

$$\rho_k \triangleq \frac{\phi_k}{\gamma_k} = \frac{f_{N,k}(\alpha, \gamma_k) - 1}{\gamma_k} \qquad (23)$$

For the user pair (U_1, U_2)

$$\rho_1 = \frac{\phi_1}{\gamma_1} = \alpha \quad \text{and} \quad \rho_2 = \frac{\phi_2}{\gamma_2} = \frac{1 - \alpha}{1 + \alpha\gamma_2} \qquad (24)$$

The case of greater fairness occurs when each user uses the same proportion of your total SINR, that is, $\rho_1 = \rho_2$. Therefore, one obtains the following equation,

$$\gamma_2\alpha^2 + 2\alpha - 1 = 0 \qquad (25)$$

Equation 25 has only one positive solution, which is given by

$$\alpha = \frac{\sqrt{1 + \gamma_2} - 1}{\gamma_2} \qquad (26)$$

Note that the presented fairness criterion ($\rho_1 = \rho_2$) follows the principle of the Broadcast Channel [4]. First, it is guaranteed that the user with smaller channel gain (U_2) can obtain the minimum information required, in this case, the NOMA rate must be at least equal to the data rate obtained in OMA ($R_{O,2} \leq R_{N,2}$). Second, the user with the highest channel gain (U_1) should receive the information destined to U_2 plus some additional information.

The same value of α in (26) is also adopted in [13] for the PA coefficient, but this choice is made in order to maximize the sum of the rates, respecting the conditions discussed in Property 4.1. The authors of [13] do not make any evaluation of alpha fairness. However, the search for a α value that maximizes the spectral efficiency could lead to a situation of injustice among users, since the sum of the rates is an increasing function of α, and the increase of this coefficient benefits only the user with higher channel gain. Therefore, it is necessary to have an analysis of fairness related to the power allocation.

It is shown in the following that the value of α given by (26) provides the highest spectral efficiency, respecting the limits imposed by (15), and also satisfies the proposed fairness criterion. In this case, user U_2 in NOMA reaches the same rate achievable in OMA for downlink.

6 Numerical Analysis

In order to perform the numerical analysis, a system simulation was performed based on the Monte Carlo technique, following the guidelines given in [14]. The simulation scenario is composed of a grid of 19 sites with three sectors each have 57 cells. The total bandwidth per cell was 10 MHz for a carrier frequency of 2 GHz. The distance between the BSs is 500 m and the transmission power is 46 dBm. The simulation considered large scale losses (propagation loss and shadow) and also small scale losses (multiple path fading). The traffic model is the full buffer, which simulates the time of highest movement in the system cell.

When the simulation begins, the resources (subbands and power) are equally distributed among the pairs. The duration of a drop or snapshot is one second, 1000 times of one Transmission Time Interval (TTI) of one millisecond. During a snapshot, the characteristics of the environment in large scale, such as shadowing and user position doesn't change. However, a variation in small scale is permitted for each TTI, due to multi path fading.

At the end of a snapshot of the simulation, the statistics are accounted for and the users are disconnected and removed from the scenario. For each new

executed snapshot, the UEs are distributed to new positions. The simulation performed 10000 Monte Carlo events in each scenario.

During the simulation $t_{k,m}$ is calculated, which is the individual rate obtained by the k-th UE allocated to the m-th sub-band of the cell, considering all variations of the multiple access techniques investigated. From $t_{k,m}$, the spectral efficiency of the cell η is computed, as well as, the sample mean of user throughput $\bar{\mathbf{t}}$, which are given respectively by:

$$\eta = \frac{1}{W} \sum_{m=1}^{M} \sum_{k=1}^{2} t_{k,m}, \qquad (27)$$

$$\bar{\mathbf{t}} = \frac{1}{2M} \sum_{m=1}^{M} \sum_{k=1}^{2} t_{k,m} \qquad (28)$$

At the end of the simulation, approximations of the Cumulative Distribution Function (CDF) are obtained, given by $P[X < x]$, in which x is the value of the measure used in the evaluation and X is a Random Variable (R.V.) that represents the values resulting from the simulation.

Considering measures η and $\bar{\mathbf{t}}$, CDF values between 0% and 5% return the worst throughput obtained, which are attributed to the UEs with the worst SINR conditions. The cell edge user spectral efficiency is defined in [15] as the 5% point of the CDF of the normalized user throughput. Similarly, the highest values of spectral efficiency are obtained by taking the 95% point of the CDF of the normalized user throughput, these values are attributed to the nearest UE of the BS. The average spectral efficiency is computed from the probability distribution extracted from the CDF.

The evaluation of the fairness level among the throughputs is provided for users under different multiple access technique using the Jain index [16] given by,

$$\mathcal{J}(\mathbf{x}) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2} \qquad (29)$$

The Jain index expresses the level of fairness between the distribution of resources to n individuals, in which x_i is a measure associated with resources allocated to the i-th individual. For the case of higher equality in resource distribution, the index is $\mathcal{J}(\{x_1, x_2, \ldots, x_n\}) = 1$. In the case of higher inequality, in which only one individual holds all the resources, the index assumes the value $\frac{1}{n}$.

The fairness measure among the pairs is calculated from the sum $p_m = t_{1,m} + t_{2,m}$ of the users allocated in the m-th sub-band, and the fairness index calculated by $\mathcal{J}(\{p_1, p_2, \ldots, p_M\})$. Based on the criterion defined in Section 5, the fairness index provided by the PA among NOMA users is evaluated from the

difference between the throughput obtained when the user is allocated exclusively on the sub-band, and the NOMA throughput obtained when the users share a sub-band.

7   Simulation Results

The performance of the PA technique presented in Section 5, referenced in this section as PA fair, is evaluated by computational simulations. Comparisons are presented with the fixed coefficient PA method ($\alpha = 0.2$), referenced as PA Fix. The fixed value of α is chosen from results of previous works [11], [6]. For both methods of power allocation, the sort-based user pairing method (scheme 1), presented in [13], has been used.

Figure 2 displays the cell edge user throughput obtained, close to the BS user throughput and the average user throughput, indicating that an increase in the number of UEs in the cell causes a reduction in the individual user rates. This behavior is expected since the total transmission power and the bandwidth of the cell are kept constant throughout the simulations.
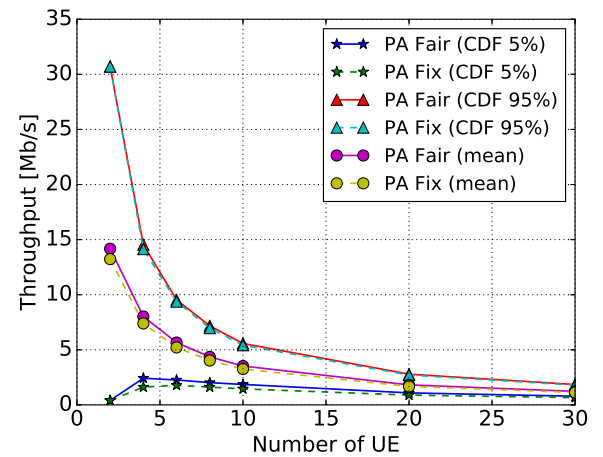

Figure 2. User throughput for PA fair and PA Fix coefficients

The values obtained for cell edge user spectral efficiency, close to the BS user spectral efficiency and the average spectral efficiency, are shown in Figure 3 as a function of the number of UE per cell. Different from the behavior of individual user throughput, the cell spectral efficiency increases as the number of UEs grows. This indicates that the frequency and power resources are underutilized when there are few users in the cell, and that the resources can be better utilized using the proposed power allocation coefficient.

Note that for the region near the BS the spectral efficiency decreases slowly with the increase of connected UEs. This reduction is caused by the increase
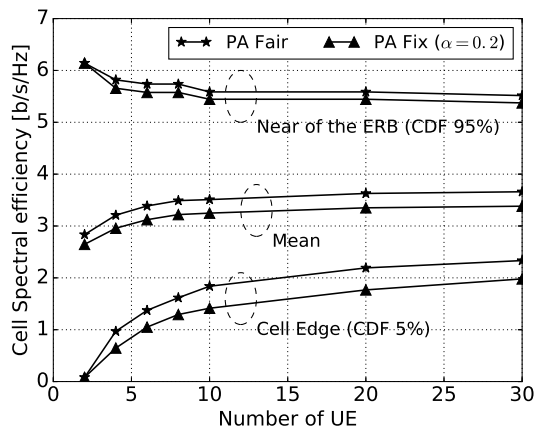
Figure 3. Cell Spectral Efficiency for fair PA and fixed coefficient PA

in the number of users, which balances the distribution of resources within the cell, reducing the large differences in channel gain experienced when there is a small number of users located close to the BS. Another situation that favors the occurrence of maximum efficiency is the low level of interference from other cells when there are few users in the system.

The results show that the PA fair technique satisfies the requirements of the spectral efficiency per cell established in [15], which is 2.6 bits/s/Hz for the micro-cell and 2.2 bits/s/Hz for urban coverage. In the same way, it is verified that the requirements for cell edge user spectral efficiency of 0.075 bits/s/Hz for micro-cell and 0.06 bits/s/Hz for urban coverage are also met.

Figure 4 presents a comparison of the level of justice for peers and users. Note that in addition to the best levels of spectral efficiency, the fair power allocation method also provides better fairness standards. Except for the case of only two UEs per cell, the fairness index among users increases with an increasing number of UEs.

Simulations were performed varying the BS transmission power, to evaluate the fairness levels provided by each technique under different scenarios of energy consumption and interference. The results are shown in Figure 5 for the case of ten users per cell. It is observed that an increase of the transmission power implies in an increase of the fairness levels for users' throughput. However, for power transmission larger than 35 dBm, the Jain index undergoes a slight decrease. This is due to an increased interference from other cells, which limits the rates achievable by users.

The PA technique with fixed coefficient presents good performance, and is a good alternative when the BS is not aware of the conditions of the users link. Nevertheless, the results show that with low
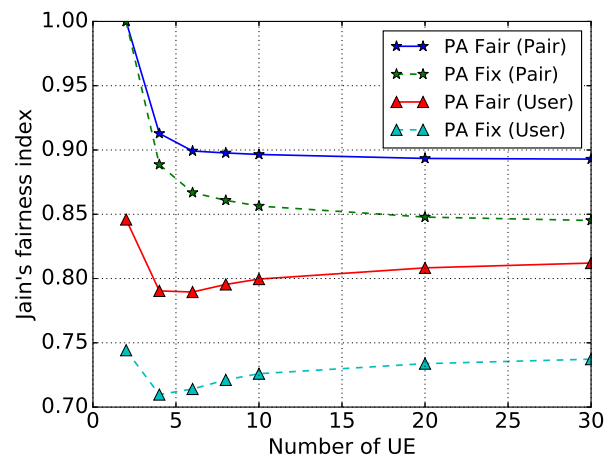

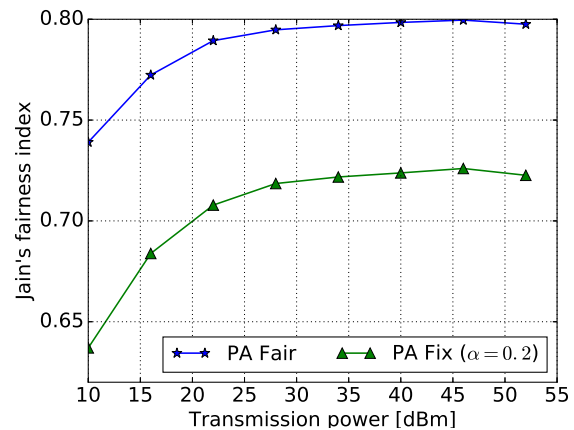**Figure 4**. Fairness index for pairs and users from simulations

Figure 5. Fairness index for pairs and users from simulations with ten users per cell, and power transmission variable

computational cost it is possible to implement the PA Fair, providing an increase in fair rate, and a more efficient use of the spectrum in the cell coverage region.

8 Conclusion

A study of power allocation in NOMA was presented in this article. It proposes a power allocation coefficient based on a low complexity fairness criterion. This method requires the BS to be aware only of the channel gain of the user U_2 of the NOMA pair. The simulation results show that the proposed PA method allows to increase the cell spectral efficiency and to offer good fairness levels, even when the number of users per cell grows.

For future work, the authors intend to evaluate efficient methods of pairing users and power allocation in the uplink of mobile communication systems. In addition, it the authors intend to study the limits imposed on NOMA techniques due to detection using

SIC.

Acknowledgment

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