User-Pairing Scheme in NOMA Systems: A PSO-Based Approach

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Abstract. Non-orthogonal multiple access (NOMA) is considered a promising technology for improving the spectral efficiency in fifth generation communication systems. In contrast to orthogonal multiple access (OMA), NOMA allows to allocate one frequency channel to multiple users at the same time within the same cell. Basically, this is possible through power-domain superposition coding (SC) multiplexing at transmitter and successive interference cancellation (SIC) at receiver. For this reason, either an optimal power allocation scheme and an optimal user-aggregation policy result to have a key role on NOMA systems, especially in power constrained scenarios like disaster communications. In this paper, a particle swarm optimization (PSO)-based approach for user aggregation in NOMA systems is presented. The efficiency of this approach in finding the optimal aggregation scheme which require the minimum transmission power, maintaining the quality of service (QoS) constraint of each user, is evaluated through simulations, providing comments and remarks about the obtained results.

Keywords: NOMA · PSO · Sub-channel mapping · User-pairing

1 Introduction

During the last decade, the diffusion of powerful multimedia devices, such as smartphones and tablets, has grown exponentially, creating the need for a new cellular technology referred to as 5G [7,11,18].

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An important aspect, used to improve the system capacity in cellular mobile communications, is the design of the multiple radio access technology (M-RAT). Nowadays, such multiple access technologies can be categorized into two different classes: *(i)* orthogonal multiple access (OMA) and *(ii)* non-orthogonal multiple access (NOMA).

Frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency-division multiple access (OFDMA) are examples of OMA schemes. In contrast to OMA, NOMA allows to allocate one frequency channel to multiple users at the same time within the same cell, offering a number of advantages which permit to label NOMA as a promising multiple access scheme for future radio access networks [2,9,14–16,19,20,23].

Since the basic principle of NOMA is to serve multiple users by power-domain superposition coding (SC) multiplexing at transmitter and successive interference cancellation (SIC) at receiver, one of the main challenges of this multiple access technique is represented by the power allocation scheme adopted by the transmitter. The problem of optimal power allocation for NOMA systems, with respect to different network performances maximization like energy efficiency maximization and maximum throughput, has been widely investigated in literature [5,6,21,22,24–26]. However, another aspect which represents a key factor for NOMA system performance, is the user-aggregation policy adopted for multiplexing users along different sub-channels [3].

To the best of our knowledge, at date, most of the works on NOMA face this aspect pairing at most two users per sub-channel [4,8,17]. One of the most extensive study can be recognized in [27], where a general scheme for aggregate more than two users into a single sub-channel is provided. Generally, the optimization process for user-pairing and sub-channel mapping in NOMA systems is represented by a mixed integer-linear problem (MILP) which, even if small, may be hard to solve. Under this perspective, this paper proposes and evaluates the performance of a particle swarm optimization (PSO) approach for user-aggregation which require the minimum transmitting power.

2 Introduction to NOMA Systems

In this section, some NOMA basics are presented. It is assumed that a base station (BS) serves N users located within its coverage area. Without loss of generality, it is also supposed that *(i)* both transmitter and receivers are equipped with a single antenna, and *(ii)* users' channel coefficient are ordered in a ascending manner, i.e., $0 < |h_1|^2 \leq |h_2|^2 \cdots \leq |h_N|^2$. In downlink the BS serves the N users employing power-domain SC multiplexing. Then, the signal received by user i can be expressed as:

$$y_i = h_i \cdot x + w_i; \quad \forall\, i = 1 \cdots N; \tag{1}$$

where $x = \sum_{i=1}^{N} \sqrt{P\beta_i} S_i$ is the superimposed signal containing all S_i messages, h_i denotes the channel coefficient, and w_i represents the noise term with spectral density σ^2. In particular, since $\sum_{i=1}^{N} \beta_i = 1$, the transmitter employ a total amount of transmitting power equal to P. Each user implement the SIC iteratively, decoding signals transmitted to users with weaker channel condition firstly and subtracting them from superimposed received signal. Then, the signal obtained from this subtracting process is used to decode its own related message. Taking that into account and supposing that $\|S_i\|^2 = 1$, the achievable rate in downlink for user i can be expressed as:

$$R_{i,DL} = \log_2\left(1 + \frac{\beta_i P|h_i|^2}{P|h_i|^2 \sum_{k=i+1}^{N} \beta_k + \sigma^2}\right), \tag{2}$$

As one can note, only the noise spectral density is present in Eq. (2) when $i = N$, since the messages of users $i < N$ have been deleted through SIC.

3 User-Aggregation Problem Formulation

Considering Eq. (2), in order to guarantee a minimum quality of service (QoS) to user i, i.e., $R_{i,DL} \geq R_i^{min}$, the minimum amount of power P_i^{min} which should be allocated to that user is formulated as:

$$P_i^{min} \geq A_i \times \left(\sum_{k=i+1}^{N} P_k + \frac{\sigma^2}{|h_i^2|}\right), \tag{3}$$

in which $P_i = P\beta_i$ and $A_i = \left(2^{R_i^{min}} - 1\right)$. Supposing that all the users have the same QoS requirements, i.e., $A_N = A_{N-1} = \cdots = A_1 = A$, Eq. (3) can be written as:

$$P_i^{min} \geq \begin{cases} A \times \frac{\sigma^2}{|h_N|^2} = P_N^{min}, & i = N; \\ A \times \left(\sum_{k=i+1}^{N} P_k + \frac{\sigma^2}{|h_k^2|}\right), & i < N; \end{cases} \tag{4}$$

In particular, after some mathematical manipulations, the second case can be expressed as follow:

$$P_i^{min} \geq A \times P_N + A \times \sum_{k=i+1}^{N-1} P_k + P_N^{min} \frac{|h_N|^2}{|h_k|^2}. \tag{5}$$

Then, the total amount of power required in order to guarantee the QoS of all users is:

$$P_{tot} = \sum_{i=1}^{N} P_i^{min} \geq \sum_{i=1}^{N-1} A \times P_N^{min} + A \times \sum_{i=1}^{N-1} \sum_{k=i+1}^{N-1} P_k + P_N^{min} \times \sum_{i=1}^{N-1} \frac{|h_N|^2}{|h_i|^2} + P_N^{min}. \tag{6}$$

Grouping by common factors and observing that the first term is independent of index i, the following expression is obtained:

$$P_{tot} \geq P_N^{min} \times \left((N-1) \times A + 1 + \sum_{i=1}^{N-1} \frac{|h_N|^2}{|h_i|^2} \right) + A \times \sum_{i=1}^{N-1} \sum_{k=i+1}^{N-1} P_k. \quad (7)$$

Then, this represents the minimum amount of power which is necessary to use in order to guarantee the QoS of all users multiplexed within the same sub-channel. This amount of energy strongly depends from user aggregation and sub-channel mapping process. Supposing that N users should be multiplexed along M independent sub-channels, and indicating with $\mathbf{U} \in \{0;1\}^{N \times M}$ the sparse matrix in which the element $u_{i,j}$ is equal to 1 if user i is allocated to sub-carrier j and 0 otherwise, the optimization problem is formulated as:

$$\min_{\mathbf{U}} \quad P_{tot} \; ; \quad (8a)$$

$$\text{s.t.} \quad R_{i,DL} \geq R_i^{min}, \quad \forall\, i = 1 \cdots N; \quad (8b)$$

$$\sum_{j=1}^{M} u_{i,j} = 1, \quad \forall\, i = 1 \cdots N; \quad (8c)$$

The constraint (8b) represents the minimum QoS requirement of each user. The constraint (8c) makes sure that each user will be multiplexed only into one sub-channel. Since this type of problem represents a MILP problem, in order to find an optimal solution, a PSO-based approach, which respect to other heuristic approaches has shown a more promising behaviour [10], is proposed.

4 A Particle Swarm Optimization (PSO) Approach for Optimal User-Pairing

PSO is one of metaheuristic optimization technique inspired by natural life behaviour like bird flocking and fish schooling [1,12]. It consists in a set of a predefined number, say N_p, of particles with a position X_i and a velocity V_i in a dimensional space of dimension D. Iteratively, each particle, which represents a solution of the optimization problem, is evaluated through a fitting function, obtaining the personal best of the particle, i.e., $Pbest_i$. This $Pbest_i$ is compared with the global best value, i.e., $Gbest$. After this comparison each particle adjusts its own position and velocity along each dimension according with the following equations:

$$V_{i,d}(t) = w \cdot V_{i,d}(t-1) + c_1 \cdot r_1 \cdot (Xpbset_{i,d} - X_{i,d}(t-1)) + c_2 \cdot r_2 \cdot (Xgbest_{i,d} - X_{i,d}(t-1)) \;, \quad (9)$$

and

$$X_{i,d}(t) = X_{i,d}(t-1) + V_{i,d}(t) \;, \quad (10)$$

where (9) and (10) represent velocity and position along dimension d, respectively, w is the inertial weight, c_1 and c_2 are two non-negative constants and r_1 and r_2 are two different uniformly random distributed numbers in the range $[0, 1]$.

As in [13], in this paper the initial set of particle has been created in a random fashion. The fitting function for each particle is the total required power expressed by Eq. (7). Moreover, no consistent changes to the solution happened after 500 iterations. Then, in order to ensure a consistent result, the number of 700 iterations has been set as PSO stop criterion. The most important parameters for (9) have been chosen as the same in [13] and are provided in Table 1.

5 Simulation Results

As simulation scenario, it is considered a scenario in which an available bandwidth B is divided equally into M independent sub-channels used to multiplex N users. These users are distributed into a circular area of radius R according with a poisson point process (PPP). The transmitter is supposed at the center of this area. It is assumed that the channel statistics of all users along the whole bandwidth are known. The channel gain of Eq. (1) has been supposed as $h_i = d_i^{-\alpha/2} \times g_i$ where g_i follows a Rayleigh distribution, d_i represents the distance between transmitter and receiver and α is the path-loss exponent. The noise power along the whole bandwidth is $N_0 = 290 \cdot k \cdot B \cdot NF$, where k and NF are Boltzmann constants and noise figure at 9 dB, respectively. Then, the noise power in each sub-channel is N_0/M. The most relevant simulation parameters are summarized in Table 1 and all results represent the average of 10 different simulation runs. The policy efficiency (PE) has been used as index for

Table 1. Simulation parameters

Parameter	Value	Parameter	value
Cell radius (m)	200	M (average number of nodes)	100
Bandwidth (MHz)	40	Pathloss exponent α	4
N_p	50	$N_{iterations}$	200
C_1	1.4962	C_2	1.4962
w	0.7968	N number of sub-channels	[25:50]
V_{max}	0.5	V_{min}	-0.5
QoS threshold [bps/Hz]	[1:5]	σ Rayleigh	1

performance evaluation. In particular, indicating with $P_{av,R}$ the average power required through random policy, and with $O_{av,i}$ the power required through PSO policy, the PE is defined as follow:

$$PE_i = \frac{P_{av,R} - O_{av,i}}{P_{av,R}} \tag{11}$$

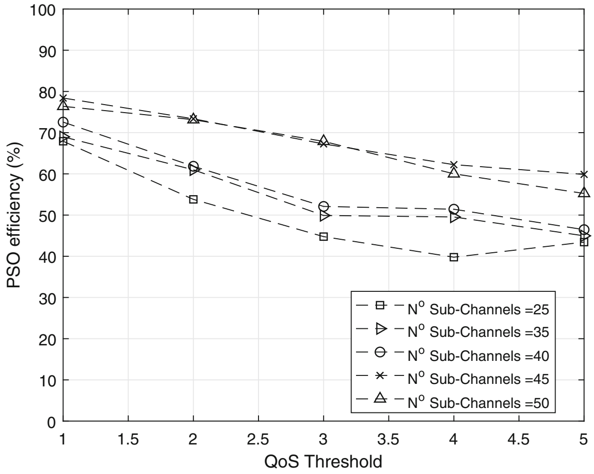

Fig. 1. Policy efficiency gain over different QoS thresholds.

In summary, this represents the reduction in power requirements by using the configuration from PSO output instead of random policy assignment.

Figure 1 shows the variation of the PE gain, expressed in percentage, by varying the QoS thresholds and the number of sub-channels. From these graphics one can note how the PE ranges from a minimum of 45% to a maximum of 80%. In addition, the PE increases by increasing the number of available sub-channels and decreases by increasing the QoS constraint. These results are in line with Eq. (7). Indeed, an increase of the QoS constraint results in an exponentially increase of the minimum required power for all the users. Moreover, reducing the number of sub-channels more users will be multiplexed in each sub-band and then, according with Eq. (5), the minimum required power for each of them increase as well. As a consequence, the total required power increase. These results confirm the efficiency of the PSO in finding the optimal configuration which require the minimum power, satisfying the QoS requirements of each user.

6 Conclusions and Future Works

Due to its advantages which can contribute to reach some requirements of next generation 5G networks, during the last few years NOMA technology has attracted the attention of the research community. In line with NOMA principle, i.e., power-domain SC multiplexing at transmitter, this paper presents a performance analysis of a PSO-based approach for user-aggregation along different sub-channels. In particular, through simulations, one can note how this user-pairing scheme is able to find the optimal configuration that permits to require the minimum transmission power, satisfying the QoS requirements of each user. However, depending on the considered scenario, the PSO-based algorithm can result in a high computational cost procedure. Thus, the design of explicit and scalable user aggregation procedures for NOMA systems represents a future direction in which this work can be served as benchmark.

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