User Fairness Maximization in Multicarrier Cognitive NOMA-WPCN with Imperfect SIC

Jhenifer de O. Melo, Pedro V. M. de Castro and Francisco R. M. Lima

Abstract— **This paper studies user fairness maximization in multicarrier Cognitive Radio (CR) Non-Orthogonal Multiple Access (NOMA) based Wireless Powered Communication Network (WPCN) under imperfect Successive Interference Cancellation (SIC) in a Internet of Things (IoT) context. The system comprises a mix of users, with one high-priority delay-sensitive user and the remaining delay-tolerant users, reflecting the diversity of IoT devices. Based on this, we investigate resource allocation in terms of subcarrier assignment to users, optimization of the time length of the first phase of WPCN operation, and SIC decoding order definition in the second phase of WPCN. An optimization problem is formulated, the optimal solution is derived and low-complexity solutions are proposed, aiming to provide reasonable alternatives for resource allocation with reduced computational cost. Simulation results demonstrate the effectiveness of the proposed suboptimal solutions in achieving good performance while maintaining low computational complexity, thus offering insights for the design and optimization of WPCN-NOMA systems in IoT and cognitive radio scenarios.**

Keywords— **Fairness, NOMA, WPCN, Multicarrier, Imperfect SIC, Cognitive Radio.**

I. INTRODUCTION

Wireless communications technologies have undergone remarkable advances in the last decades, driven by the crescent demand for greater bandwidth, greater spectral efficiency and lower latency. Furthermore, the implementation of Internet of Things (IoT) has unleashed a large number of interconnected smart devices in various applications, from home automation to smart urban infrastructure. While Fifth Generation (5G) has not yet reached its full potential, researchers are already studying beyond 5G scenarios and solutions [1].

The new advances and demands incur in significant challenges. Energy efficiency, for example, is considered a critical concern due to environmental issues and the exponential increase in the number of wireless devices [2]. In this context, Wireless Powered Communication Network (WPCN) is a potential network concept to enable the communication with low-power IoT devices by employing the concepts of Wireless Power Transfer (WPT) and Energy Harvesting (EH). In WPCN, the time frame is split into two phases. In phase 1, a Hybrid Access Point (HAP) broadcasts energy signals in Downlink (DL) by means of WPT while devices employ EH to collect energy. In phase 2, the devices transmit the information in Uplink (UL) using the collected energy in phase 1 [3].

In phase 2 of WPCN, a multiple access scheme should be employed to mitigate interference. Non-Orthogonal Multiple Access (NOMA) plays an important role in the continuous evolution of wireless communication systems, providing high spectral efficiency and multiplexing capacity for IoT devices [6]. Note that NOMA can be integrated with classical Orthogonal Frequency Division Multiple Access (OFDMA) where group of devices can be multiplexed using NOMA per Orthogonal Frequency Division Multiplexing (OFDM) subcarrier in a multicarrier NOMA context.

In order to improve even more the spectral efficiency and connection density, Cognitive Radio (CR) NOMA has been proposed where primary users have access to spectral resources with assured Quality of Service (QoS) while sharing resources with secondary users that opportunistically access spectral resources without deteriorating primary users' QoS [13]. Moreover, when assessing the performance of NOMA, important to consider the impact of imperfect Successive Interference Cancellation (SIC) where interfering signals are no perfectly canceled during the SIC procedure. The main reason for this are hardware impairments and imperfect channel estimation [4].

Single-carrier WPCN networks have been studied in the literature [8], [12]. In [8], the authors carried out a study of power and time allocation in WPCN focusing on maximizing user fairness, however, NOMA is not addressed. The formulated optimization problem was shown to be non-convex and, after applying some transformations, a convex problem was obtained and solved. Inspired by the cognitive NOMA scenario proposed in [13], in [12] the authors assumed the use of CR NOMA in WPCN, where a primary user shares resources with secondary users. The problem of maximizing the secondary user's data rate subject to the QoS of primary user assuming imperfect SIC was formulated. A solution for secondary user selection and SIC ordering was proposed.

Multicarrier NOMA have been considered by some works, but not in the context of WPCN [9], [10], [11]. In [9], the authors investigated the sum-rate and energy efficiency maximization in the UL of a multicarrier NOMA system. However, user fairness is not addressed. Nevertheless, the authors in [10] studied energy efficiency and user fairness optimization for DL. In [11], the authors conducted a power allocation study to maximize sum-rate and energy efficiency in DL of a multicarrier NOMA system.

Motivated by the research gap identified in the previous articles, we assume in this work a multicarrier WPCN with CR NOMA assuming imperfect SIC aiming at maximizing the fairness among secondary users while guaranteeing the QoS to the primary user. The time length for phase 1, pairing

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between primary and secondary users, and SIC decoding order are optimized.

The rest of this document is organized as follows. In section II, we present the system model and its main assumptions. In section III, the studied problem is formulated in optimization form considering all restrictions specified in the system model. The optimal solution is also proposed. Then, we propose suboptimal solutions in section IV to solve the optimization problem at a low computational complexity. Thereafter, a performance evaluation of the proposed solutions is shown section V. Lastly, in section VI, we present the main conclusions of this work.

II. SYSTEM MODEL

We consider a WPCN that consists of a circular cell where users are evenly distributed around a central HAP, incorporating CR NOMA under imperfect SIC. The time frame is a periodic time interval divided into an integer N of time slots, which are separated into two distinct phases: WPT/energy harvesting and UL data transmission. In the first phase, users have their batteries recharged by radio frequency waves coming from the HAP. In the second phase, users send their data to the HAP using the energy collected in the first phase. There are $M+1$ users in total, including a primary user U_0 that is a delay-sensitive user that has priority over the others. The remaining M users have greater delay tolerance and are considered secondary users U_i, where $i \in \{1, 2, ..., M\}$. We assume a multicarrier network with S orthogonal subcarriers where $s \in \{1, 2, \cdots, S\}$.

In the assumed CR model, due to the high priority and strict delay requirements of the primary user, U_0 gets assigned all subcarriers. Each subcarrier is shared with only one secondary user U_i employing NOMA. Each secondary user U_i can use at most L subcarriers, with $L < S$. It is desirable that each secondary user is served with at least one subcarrier, so $L = S - M + 1$. In the WPT stage, the power collected by any user j, where $j \in \{0, 1, 2, ..., M\}$, on subcarrier s using n^{e} time slots for energy harvesting is defined as

$$P_{j,s,n^{\mathrm{e}}}^{\mathrm{WPT}} = P \, \eta \, g_{j,s} \, \frac{n^{\mathrm{e}}}{N - n^{\mathrm{e}}}, \tag{1}$$

where P is the power emitted by the transmitter, η is the energy harvesting efficiency coefficient ($0 \leq \eta \leq 1$) and $g_{j,s}$ is the channel gain between HAP and user j in UL/DL (assuming reciprocity) in subcarrier s.

The total transmit power of any user j in phase 2 is given by $P_{j,n^{\mathrm{e}}}^{\mathrm{total}} = \sum_{s=1}^{S} P_{j,s,n^{\mathrm{e}}}^{\mathrm{WPT}}$. In UL, the primary user U_0 transmits on each subcarrier employing equal power allocation among subcarriers, i.e., $P_{0,s,n^{\mathrm{e}}} = P_{0,n^{\mathrm{e}}}^{\mathrm{total}}/S$. Moreover, the transmission power of a secondary user U_i per subcarrier is equal to the total power collected by U_i divided by the maximum number of subcarriers that a secondary user can use, that is, $P_{i,s,n^{\mathrm{e}}} = P_{i,n^{\mathrm{e}}}^{\mathrm{total}}/L$.

As we apply NOMA in the second phase, two possible decoding orders in SIC are possible for each subcarrier at the HAP: $p = 1$ when the signal from the secondary user is firstly decoded and then the signal from the primary one, and $p = 2$, otherwise. The achievable data rate of the i-th secondary user on subcarrier s when n^{e} time slots are used for energy harvesting and the decoding order p is adopted in SIC, is given by

$$r_{i,s,n^{\mathrm{e}},p} = \begin{cases} \dfrac{B}{S} \dfrac{(N - n^{\mathrm{e}})}{N} \log_2 \left(1 + \dfrac{P_{i,s,n^{\mathrm{e}}} \cdot g_{i,s}}{P_{0,s,n^{\mathrm{e}}} \cdot g_{0,s} + \sigma^2}\right), \\ \text{if } p = 1; \\ \dfrac{B}{S} \dfrac{(N - n^{\mathrm{e}})}{N} \log_2 \left(1 + \dfrac{P_{i,n^{\mathrm{e}}} \cdot g_{i,s}}{P_{0,s,n^{\mathrm{e}}} \cdot g_{0,s} \cdot \epsilon + \sigma^2}\right), \\ \text{if } p = 2; \end{cases} \tag{2}$$

where B is the channel bandwidth, ϵ is the Residual Error Factor (REF) due to imperfect SIC with $0 \leq \epsilon$, and σ^2 is the thermal noise power.

On the other hand, the primary user's data rate on subcarrier s when paired with the i-th secondary user, n^{e} time slots are used in energy harvesting and the decoding order p is applied in SIC, is given by

$$r_{i,s,n^{\mathrm{e}},p}^{0} = \begin{cases} \dfrac{B}{S} \dfrac{(N - n^{\mathrm{e}})}{N} \log_2 \left(1 + \dfrac{P_{0,s,n^{\mathrm{e}}} \cdot g_{0,s}}{P_{i,s,n^{\mathrm{e}}} \cdot g_{i,s} \cdot \epsilon + \sigma^2}\right), \\ \text{if } p = 1; \\ \dfrac{B}{S} \dfrac{(N - n^{\mathrm{e}})}{N} \log_2 \left(1 + \dfrac{P_{0,s,n^{\mathrm{e}}} \cdot g_{0,s}}{P_{i,s,n^{\mathrm{e}}} \cdot g_{i,s} + \sigma^2}\right), \\ \text{if } p = 2. \end{cases} \tag{3}$$

III. PROBLEM FORMULATION AND OPTIMAL SOLUTION

Before defining the studied optimization problem, we need to define the optimization variable. We assume that $x_{i,s,n^{\mathrm{e}},p}$ as a binary optimization variable that assumes the value 1 if the secondary user i is paired with the primary one at subcarrier s with the SIC decoding order p, and 0 otherwise. The fairness maximization problem is formulated as

$$\max_{x_{i,s,n^{\mathrm{e}},p}} \left\{ \min \left(\sum_{s=1}^{S} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} r_{i,s,n^{\mathrm{e}},p} \, x_{i,s,n^{\mathrm{e}},p}, \; \forall i \right) \right\}, \tag{4a}$$

$$\text{s.t.} \; \sum_{i=1}^{M} \sum_{s=1}^{S} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} r_{i,s,n^{\mathrm{e}},p}^{0} \, x_{i,s,n^{\mathrm{e}},p} \geq R_0, \tag{4b}$$

$$\sum_{s=1}^{S} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} x_{i,s,n^{\mathrm{e}},p} \leq L, \; \forall i, \tag{4c}$$

$$\sum_{i=1}^{M} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} x_{i,s,n^{\mathrm{e}},p} = 1, \; \forall s, \tag{4d}$$

$$\sum_{i=1}^{M} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} n^{\mathrm{e}} \, x_{i,s,n^{\mathrm{e}},p} = \sum_{i=1}^{M} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} n^{\mathrm{e}} \, x_{i,1,n^{\mathrm{e}},p}, \; \forall s > 1. \tag{4e}$$

The objective function defined by (4a) represents the maximization of the minimum data rate of the secondary users (max-min fairness). The constraint (4b) imposes that the primary user should have its QoS requirement satisfied, i.e., its data rate should be equal to or greater than its minimum requested data rate R_0. Constraint (4c) assures that each secondary user can be paired with the primary one in at most L subcarriers. Constraints (4d) and (4e) guarantee that each subcarrier is assigned to only one secondary user and that only one decoding order p and number of time slots for energy harvesting n^{e} are chosen.

The formulated problem is integer and non-linear due to the objective function. In order to obtain the optimal solution, consider the following algebraic manipulation. The max-min expression in the objective function can be replaced by adding a new variable and the introduction of a new constraint to the problem as follows:

$$\max_{x_{i,s,n^{\mathrm{e}},p};\,\theta} \{\theta\}, \tag{5a}$$

$$\text{s.t.} \sum_{s=1}^{S} \sum_{n^{\mathrm{e}}=1}^{N-1} \sum_{p=1}^{2} r_{i,s,n^{\mathrm{e}},p}\, x_{i,s,n^{\mathrm{e}},p} \geq \theta, \forall i, \tag{5b}$$

$$\text{(4b)-(4e)}, \tag{5c}$$

where θ is an auxiliary variable used to linearize the problem and corresponds to the minimum data rate of secondary users.

Now, problem (5) becomes an Integer Linear Program (ILP) that can be optimally solved by standard solvers based on the Branch-and-Bound (BB) method [14]. The worst-case computational complexity of BB is dominated by the number of linear (continuous) subproblems that should be solved that, in this case, is given by $\sqrt{2}^{l}$ where l is the number of variables in the problem. As we have $2MNS$ variables, the worst-case complexity is given by $O\left(2^{MNS}\right)$, i.e., exponential in terms of the problem variables.

IV. Low-Complexity Solutions

Motivated by the high computational complexity to obtain the optimal solution, we proposed in this section low-computational alternatives to solve the formulated problem.

The main reasoning in our proposal is to improve the minimum individual data rate of the secondary users U_i iteratively, while still respecting the QoS guarantees for the primary user U_0. Initially, we assume that the decoding order $p = 2$ is applied to all subcarriers, i.e., U_0 has its signal decoded first and experiences interference from the secondary users occupying each subcarrier. As the number of slots in each frame is not high, in general, exhaustive search is applied for n^{e}. The steps of the proposed solution are summarized in Algorithm 1.

Algorithm 1: Dynamic subcarrier allocation for the user fairness problem

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1  Let $V$ be a variable that identifies the type o suboptimal solution that was chosen. The possible values are 1 or 2 for suboptimal solutions 1 and 2, respectively.
2  Let $R_0$ be the data rate requested by the primary user;
3  Let $R_{\min}(n^{\mathrm{e}})$ be the minimum data rate of secondary users when an integer $n^{\mathrm{e}}$ is used to harvest energy;
4  for $n^e = 1 : N - 1$ do
5      Calculate the powers collected from secondary users, $P^{\mathrm{total}}_{i,n^{\mathrm{e}}}$;
6      Define an initial priority queue of secondary users, $\{U_1, U_2, ..., U_M\}$, where $U_1$ is the user with the lowest collected power and highest priority, $U_2$ is the user with the second lowest power collected and the second highest priority, and so on;
7      Let $S_{avail} = \{1, 2, 3, ..., S\}$ be the set of available subcarriers for allocation;
8      for i=1:M do
9          if $V = 1$ then
10             For the secondary user $U_i$, allocate the subcarrier in which the channel gain $g_{i,s}$ is the highest and remove this subcarrier from $S_{avail}$;
11         end
12         if $V = 2$ then
13             For the secondary user $U_i$, allocate from the set $S_{avail}$ the subcarrier whose channel gain of the primary user is the highest and then remove such subcarrier from $S_{avail}$;
14         end
15     end
16     while $S_{avail} \neq \emptyset$ do
17         Calculate current data rates for secondary users considering $p = 2$;
18         Select the secondary user with the lowest total data rate in the instance and allocate from the set $S_{avail}$ the subcarrier whose channel gain of the primary user is highest and then remove such subcarrier from $S_{avail}$;
19     end
20     With the allocation done so far, calculate the primary user's instantaneous $R_0^{\mathrm{inst}}$ data rate;
21     if $R_0^{inst} < R_0$ then
22         Let $S_{p=2}$ be a set of subcarriers in which the decoding order is $p = 2$;
23         while $R_0^{inst} < R_0$ do
24             if $S_{p=2} = \emptyset$ then
25                 break;
26             end
27             Select the secondary user with the highest data rate in the last instance, recalculate its data rate now considering $p = 1$ on its worst subcarrier (where its channel gain is lowest), and then remove that subcarrier from $S_{p=2}$;
28         end
29     end
30     Calculate the lowest data rate of secondary users, $R_{\min}(n^{\mathrm{e}})$;
31 end
32 The solution will be the largest $R_{\min}(n^{\mathrm{e}})$ $\forall n^{\mathrm{e}}$.
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Next, we provide more details about Algorithm1. Initially, we assume that all subcarriers are assigned to the primary user. In line 3, different values for n^{e} are evaluated exhaustively. Then, in line 5 the secondary users are sorted according to their collected power in the first phase of WPCN where the users with lower collected power have higher priority. After that, from lines 8 to 15, each secondary user, according to its priority, is chosen to share a subcarrier with the primary user. Here, we have two variants of the proposed algorithm. In the first one, the secondary user gets assigned its best subcarrier, while in the second variant the secondary user gets assigned the best subcarrier of the primary user, among the remaining ones. In the first variant the focus is to improve secondary user data rates whereas in the second one is to protect the QoS of the primary one. Note that, as $p = 2$, choosing the subcarrier where the primary user has the strongest gain still keeps a good Signal to Interference plus Noise Ratio (SINR) for the primary user on that subcarrier.

After that, in line 16, if there are still available subcarriers (not assigned to secondary users), the subcarriers are iteratively assigned to the secondary user with the lowest current achievable data rate. The assigned subcarriers to secondary user are the ones where the primary user has the strongest channel. After that, in line 20, the current achievable data rate of the primary user is calculated. If the primary user's QoS is met, the algorithm is finished. Otherwise, in line 27, we select the secondary user with the highest current data rate, choose its worst subcarrier and change the decoding order to $p = 1$. Note that in this case, the primary user's signal will be decoded after the secondary user's signal, improving the SINR of the primary user, thus, its data rate. These steps are repeated until the primary user's QoS is met or all the subcarriers are changed to decoding order $p = 1$. The worst-case computational complexity of Algorithm 1 is dominated by the loops on the number of time slots per frame, N, and the subcarrier assignment process. Thus, assuming $M < S$, the worst-case computational complexity is polynomial and given by $O(N\,S)$.

V. RESULTS AND PERFORMANCE EVALUATION

In this section we provide a performance evaluation of the involved algorithms by means of computational simulations employing the Monte Carlo method with 5,000 repetitions in order to assure statistical confidence. More details of the simualtions are described in the following. The system comprises a circular cell where users are uniformly distributed within a disk with an outer radius of 10 meters and an inner radius of 1 meter. The HAP is located at the center of this circumference. The channel bandwidth is 1 MHz, and the total number of time slots in a frame is $N = 20$. The channel gain between the HAP and the user U_j in subcarrier s is modeled as $g_{j,s} = 10^{-3} X_{j,s} d_j^{-3}$ where d_j represents the distance between the user U_j and the HAP in meters, and $X_{j,s}, \forall j, s$, is an independent and exponentially distributed random variable with a unit mean [12]. The channel coefficient follows the Rayleigh distribution. To mitigate significant computational costs to obtain the optimal solution, the number of secondary users, M, is set to 3, and the number of subcarriers, S, is 6. The noise power is -104 dBm, the energy harvesting efficiency η is 0.5, and the transmission power of the HAP during the energy transfer stage is 5 W. The optimal solution was obtained with the CPLEX package [14].

In our performance analysis, we compare the proposed optimal solution presented in Section III with the low-complexity ones proposed in Section IV. In the plots, the variants 1 and 2 of Algorithm 1 are identified in the plots as Suboptimal 1 and Suboptimal 2, respectively. The considered performance metrics are the primary user's outage probability and the maximum and minimum data rates of the secondary users. The first one represents how often the QoS of the primary user has been violated. The maximum and minimum data rate of secondary users allow us to assess how fair is a given solution.

In Figure 1, we have a comparison of the averages of the minimum and maximum data rates achievable for secondary users versus the minimum data rate requested by the primary user, R_0. In this plot, each solution has its R_{min} and R_{max}, which represent minimum and maximum data rate among all secondary users, respectively. The fairness increases in our model as the worst data rate among secondary users augments. First of all, we can see that R_{min} and R_{max} decrease as the primary user's QoS increases. This is expected since strict QoS demands for the primary user forces the SIC decoding order $p = 1$ be used more often, which leads to lower SINRs for secondary users. Moreover, as the user's QoS increases, the performance of the two proposed suboptimal solutions moves away from the optimal curve, which shows that both lose performance at high values of R_0. However, it should be highlighted that the optimal solution presents a much more higher computational complexity.

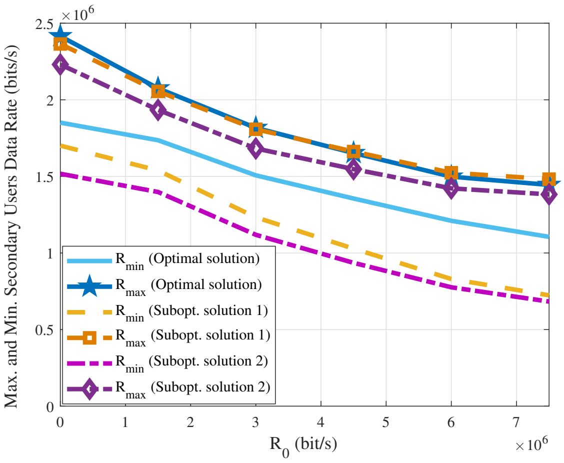

Fig. 1: Minimum and maximum data rates for secondary users versus minimum data rate requested by primary user. We assume $\epsilon = 0$.

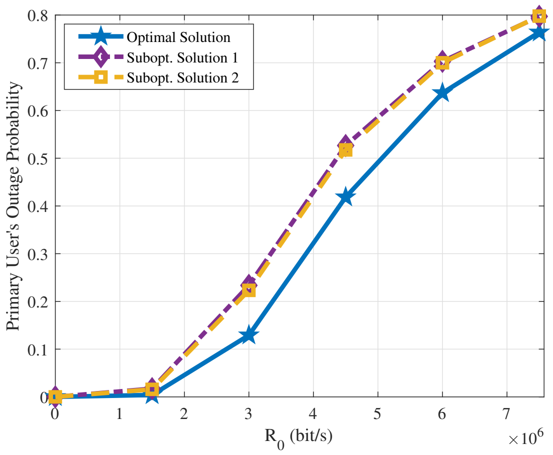

Fig. 2: Primary user's outage probability versus its requested data rate. We assume $\epsilon = 0$.

In Figure 2 we present the outage probability for the primary user versus its required QoS. As expected, all solutions increase the outage probability as the QoS of the primary user becomes more stringent. Important to notice that the difference in outage probability between the optimal and the two suboptimal ones is not higher than 10% in this plot. Furthermore, suboptimal solution 2 presents a slight advantage in terms of outage probability, even with the growth of R_0. As we explained before, this solution tends to prioritize primary user's QoS.

In Figure 3, we extend the investigation to the imperfect SIC assuming a fixed $R_0 = 200$ kbit/s. In this figure we plot the minimum and maximum data rates achieved for secondary users versus the REF for SIC decoding, ϵ. Firstly, we can see that suboptimal solution 1 presents better fairness than

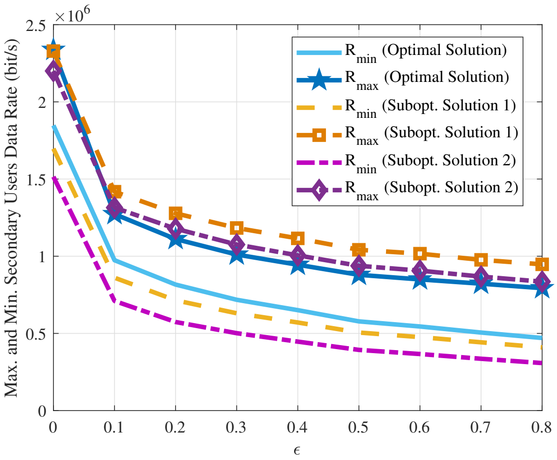

Fig. 3: Minimum and maximum data rates obtained by secondary users versus REF with $R_0 = 200$ kbit/s.

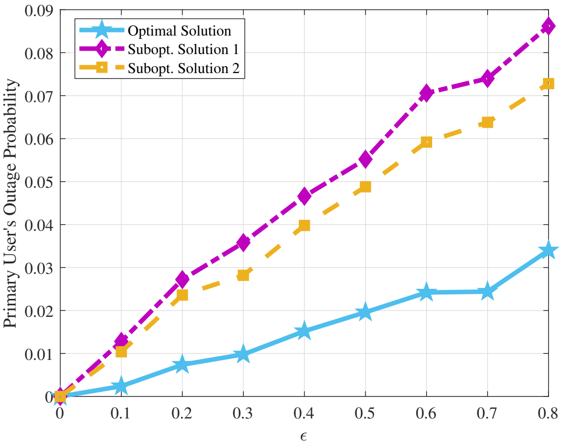

Fig. 4: Primary user's outage probability versus REF with $R_0 = 200$ kbit/s.

suboptimal solution 2. The reason for this is the subcarrier assignment in suboptimal solution 2 that prioritizes secondary users. Moreover, we can notice that R_{min} for the optimal solution and suboptimal solution 1 have only a small difference.

In Figure 4, we present the outage probability for the primary user versus REF for SIC decoding. As expected, outage probability increases with REF. Basically, as the SIC imperfection increases, lower SINRs are achieved for the signals that are lastly decoded in SIC when compared to the perfect SIC case. The performance of both suboptimal solutions is acceptable especially if we take into account the computational complexity of the optimal solution. For example, when REF is equal to 20%, the difference in probability between suboptimal solution 2 and the optimal one is of only 2%. Although the performance difference increases as REF augments, important to note that in general typical values of REF are much lower than 0.8 [4]. As suboptimal solution 2 presents a concern with the primary user's QoS satisfaction in the two parts of subcarrier allocation in Algorithm 1, its performance is expected to be better than the performance of suboptimal solution 1 in terms of primary user's outage probability.

VI. Conclusions and Perspectives

User fairness is an essential performance metric in communications systems. Therefore, in this article, we delve into exploring a multicarrier WPCN-NOMA system under imperfect SIC, focusing on maximizing secondary user's fairness while guaranteeing primary user's QoS in a cognitive radio environment. In this work, we consider the optimization of WPT time length, subcarrier assignment and user pairing. The optimal solution and two low-complexity solutions are proposed. Through computational simulations, we could observe the performance loss of the suboptimal solutions when compared to the optimal one regarding primary user's outage probability and secondary user's data rate. In summary, taking into account the high computational complexity of the optimal solution, we conclude that the suboptimal solutions present a good performance-complexity trade-off.

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