Downlink Multi-Carrier NOMA with Opportunistic Bandwidth Allocations

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***Abstract*—Multi-carrier non-orthogonal multiple access (MC-NOMA) system has been considered as a promising candidate in future wireless networks. In a MC-NOMA system, the available bandwidth of transmission is divided into several sub-bands, such that multiple users in each sub-band are served based on power-domain NOMA. Unlike the equal sub-band allocations, we propose a sum-rate maximization technique that jointly allocates the available power and bandwidth with opportunistic sharing between the sub-bands. A second-order cone program approach is exploited to deal with the non-convexity issues of the corresponding optimization problem. Simulation results reveal that the MC-NOMA system with opportunistic bandwidth allocation outperforms the scheme with the equal bandwidth allocation in terms of achieved sum-rate.**

***Index Terms*—Non-orthogonal multiple access (NOMA), Multi-carrier NOMA.**

I. Introduction

Power-domain non-orthogonal multiple access (NOMA) has been proposed as promising multiple access technique for future wireless networks [1] [2] [3]. In contrast to the conventional orthogonal multiple access (OMA) techniques, e.g., time division multiple access (TDMA) and orthogonal frequency division multiple access (OFDMA), users in power-domain NOMA are simultaneously served within the same resource block (RB) [1] [4] [5]. This can be accomplished with superposition coding (SC) at transmitter and successive interference cancellation (SIC) at receiver. With SIC, stronger users are able to decode and subtract the signals intended to weaker users prior to decoding their own signals [6] [7] [8]. However, there are several practical challenges associated with employing SIC. For example, stronger users should be able to decode the signals intended to a large number of weaker users prior to decoding their own signals which is not affordable and computationally prohibited in dense networks [9] [10].

To overcome the practical challenges in employing SIC, and thus, enabling the practical implementation of NOMA in dense networks, NOMA has been recently combined with other multiple access techniques. Examples include NOMA with conventional OMA (OMA-NOMA) techniques, including hybrid TDMA-NOMA [11], and hybrid OFDMA-NOMA [12] [8], referred to as multi-carrier NOMA (MC-NOMA). These hybrid systems have the potential capabilities to offer massive connectivity in future wireless networks. This benefit is due to the fact that different domains can be exploited to serve users in hybrid techniques [13]. Considering the OFDMA-NOMA systems, the available bandwidth for transmission (B) is divided into several sub-bands, such that different groups of users are served simultaneously in different sub-bands with the power-domain NOMA [14]. This type of OFDMA-NOMA system has been referred to as a MC-NOMA in the literature [15] [16].

Previous works on MC-NOMA in the literature assume that the available bandwidth, B, is divided *equally* (i.e., sub-bands) and allocated to different groups of users [14], [17]. This bandwidth allocation has negative impacts on the performance of such MC-NOMA systems serving to different groups of users with diverse channel conditions [18]. In other words, allocating equal bandwidths to serve different groups of users degrades the overall performance of these MC-NOMA systems [19]. To address this performance degradation, bandwidth and power allocations need to be jointly considered to enhance the performance of the MC-NOMA systems. In fact, the works in the literature consider equal bandwidth allocation, including [20], [21], and [22]. Motivated by this, we propose a sum-rate maximization (SRM) based resource allocation technique for a downlink MC-NOMA system with opportunistic bandwidth allocation. Unlike the previous works in the literature, the available power and bandwidth are *jointly* allocated to maximize the achievable sum-rate of a MC-NOMA system. However, the optimization problem corresponding to the SRM resource allocation technique is non-convex and cannot be solved using standard optimization techniques. To deal with this non-convexity issue, a novel second-order cone (SOC) program approach along with the sequential convex approximation (SCA) is utilized and the corresponding power and bandwidth allocations are determined.

The remainder of the paper is organized as follows. Section II introduces the system model of a MC-NOMA system, and

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a SRM based resource allocation technique with opportunistic bandwidth allocation technique is developed. Section III provides a detailed procedure to solve the considered SRM problem. Section IV presents simulation results to demonstrate the benefits of the proposed opportunistic bandwidth allocation. Finally, conclusions are drawn in Section V.

II. System Model and Problem Formulations

A. System Model

We consider a multi-user single-input single-output MC-NOMA system with K users. In this system, the available bandwidth for transmission, i.e., B, is divided into several sub-channels, such that the i^{th} sub-channel is denoted as $SC_i, \forall i \in \mathcal{C} \triangleq \{1, 2, \cdots, C\}$, where C is the total number of sub-channles. Note that sub-band and sub-channel carry the same meaning in this letter. Furthermore, as seen in Fig. 1, a set of K_i users $\forall i \in \mathcal{C}$ is grouped and served in SC_i, as such a sub-bandwidth (B_i) is allocated for the users in SC_i, where $B = \sum_{i=1}^{C} B_i$ and $K = \sum_{i=1}^{C} K_i$.

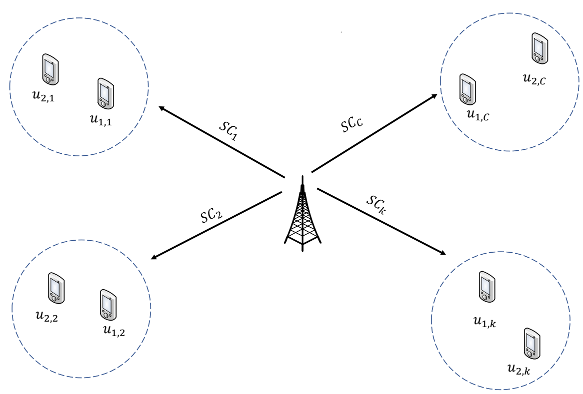

Fig. 1: Downlink MC-NOMA system with $K_i = 2$

The transmitter sends a signal x_i to serve the users grouped in SC_i, such as

$$x_i = \sum_{k=1}^{K_i} \sqrt{p_{j,i}} s_{j,i}, \tag{1}$$

where $s_{j,i}$ and $p_{j,i}$ are the symbol intended to the j^{th} user in SC_i $u_{j,i}$, and the corresponding power allocation, respectively. The received signal at $u_{j,i}, \forall i \in \mathcal{C}, \forall j \in \mathcal{K}_i \triangleq \{1, 2, \cdots, K_i\}$, is given by

$$r_{j,i} = h_{j,i} \sum_{k=1}^{K_i} \sqrt{p_{k,i}} s_{k,i} + n_{j,i}, \tag{2}$$

where $n_{j,i}$ is the additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_{j,i}^2$. Furthermore, $h_{j,i}$ is the channel coefficient between the base station and $u_{j,i}$. In this letter, the channel coefficients are modeled as $h_{j,i} = d_{j,i}^{-a} g_{j,i}$, where $d_{j,i}$ denotes the distance between $u_{j,i}$ and the base station in meters, a is the path loss exponent, and $g_{j,i}$ is the small scale fading coefficient which is assumed to be Rayleigh fading. The total transmit power at the base station can be defined as

$$P_t = \sum_{i=1}^{C} \sum_{j=1}^{K_i} p_{j,i}. \tag{3}$$

In the MC-NOMA system, the users within SC_i are ordered based on their channel strengths, such as

$$|h_{1,i}|^2 \geq |h_{2,i}|^2 \geq \cdots \geq |h_{K_i,i}|^2, \quad \forall i \in \mathcal{C}. \tag{4}$$

Based on this ordering, $u_{j,i}$ performs SIC to detect and subtract the signals intended to the weaker users $u_{j+1,i} \cdots u_{K_i,i}$ prior to decoding its own signal [23] [24]. The successful implementation of this iterative decoding can be guaranteed by imposing the following constraint [25]:

$$p_{K_i,i} \geq p_{K_i-1,i} \geq \cdots \geq p_{1,i}, \forall i \in \mathcal{C}. \tag{5}$$

Hence, the received signal at $u_{j,i}$ after performing SIC can be represented as

$$\tilde{r}_{j,i} = \left(h_{j,i} \sqrt{p_{j,i}} x_{j,i} + h_{j,i} \sum_{k=1}^{j-1} \sqrt{p_{k,i}} x_{s,i} + n_{j,i} \right). \tag{6}$$

Note that the signal to interference and noise ratio (SINR) at $u_{j,i}$ who decodes the messages intended to the weaker users $u_{d,i}$ $\forall d \in \{j+1, \cdots, K_i\}$ can be written as

$$\text{SINR}_{j,i}^{d} = \frac{h_{j,i}^2 p_{d,i}}{h_{j,i}^2 \sum_{s=1}^{d-1} p_{d,i} + B_i \sigma_{j,i}^2}. \tag{7}$$

Similarly, the signal intended to $u_{j,i}$ will be decoded at the stronger users. Thus, the SINR of the symbol $s_{j,i}$ at user $u_{j,i}$ can be defined as follows [26] [27]:

$$\text{SINR}_{j,i} = \min\{\text{SINR}_{j,i}^{1}, \cdots, \text{SINR}_{j,i}^{j}\}. \tag{8}$$

Therefore, the achieved rate at $u_{j,i}$ is written as,

$$\text{R}_{j,i} = B_i \log_2(1 + \text{SINR}_{j,i}), \forall i \in \mathcal{C}, \forall j \in \mathcal{K}_i. \tag{9}$$

Based on this rate expression, the achieved sum rate for this MC-NOMA system is given as $R = \sum_{i=1}^{C} \sum_{j=1}^{K_i} \text{R}_{j,i}$. This rate definition can be applied for a MC-NOMA system with any number of users in each sub-channel. However, for sake of simplicity, we assume that the number of users in each group is two, i.e., $K_i = 2$. This assumption reduces the computational complexity of SIC while enabling practical implementation of the proposed MC-NOMA technique with opportunistic bandwidth allocation.

B. Problem Formulation

For this MC-NOMA system, we develop a sum-rate maximization based resource allocation technique. In particular, we aim to maximize the achievable sum-rate with joint power and bandwidth allocation. This joint resource allocation problem can be formulated as follows:

$$OP_1 \underset{\{p_{j,i},B_i\}_{i=1}^{K}}{\text{maximize}} \quad \sum_{i=1}^{C}\sum_{j=1}^{K_i} \mathrm{R}_{j,i} \tag{10a}$$

$$\text{subject to} \quad P_t = \sum_{i=1}^{C}\sum_{j=1}^{K_i} p_{j,i} \leq P_{max}, \tag{10b}$$

$$p_{K_i,i} \geq p_{K_i-1,i} \geq \cdots \geq p_{1,i}, \forall i \in \mathcal{C}, \tag{10c}$$

$$\sum_{i=1}^{C} B_i \leq B. \tag{10d}$$

Note that the previous works in the literature have considered equal sub-band allocations, i.e., $B_i = B/C$. To further improve the performance of this equal sub-band allocation scheme, we propose a MC-NOMA system with opportunistic bandwidth allocation, It is obvious that the optimization problems OP_1 is non-convex in nature and it cannot be solved directly via available softwares. Furthermore, allocating the design parameter, B_i, jointly with other design parameters introduces additional computational complexity to the problem. To deal with these non-convexity issues, we develop an effective approach in the following section.

III. Proposed Methodology

In this section, we present a SOC program approach and SCA to solve the joint non-convex optimization problem OP_1. As each sub-band is assigned to two users, the grouping strategy is a crucial factor for the overall system performance. In particular, the optimal grouping strategy can be only achieved using the exhaustive search, which, however, has a high computational complexity that grows exponentially with the number of users. In this letter, we employ a clustering algorithm considered in [6] [11]. In this clustering, users with higher difference in channel strengths are grouped together, which, as a result, facilitates the practical implementation of SIC. By taking into account the practical implementation, we choose two users per each cluster in the simulation. However, the analysis provided in this manuscript is still valid for any number of users per cluster.

A. Proposed Algorithm

We exploit the SCA technique to deal with the non-convexity issue of OP_1. With SCA, non-negative slack variables, namely $z_{i,j}$, $\rho_{j,i}$, and $\theta_{j,i}$, are introduced to approximate the non-convex objective function, i.e., $R_{i,j}$, such as

$$B_i \log_2(1 + \mathrm{SINR}_{j,i}) \geq z_{j,i} \tag{11a}$$

$$\log_2(1 + \mathrm{SINR}_{j,i}) \geq \rho_{j,i}, \tag{11b}$$

$$(1 + \mathrm{SINR}^{d}_{j,i}) \geq \theta_{j,i}, \tag{11c}$$

$$\theta_{j,i} \geq 2^{\rho_{j,i}}. \tag{11d}$$

To deal with the non-convexity of (11c), we first introduce a slack variable $\chi_{j,i}$ as follows:

$$\frac{h^2_{j,i} p_{d,i}}{h^2_{j,i}\sum_{s=1}^{d-1} p_{d,i} + B_i\sigma^2_{j,i}} \geq \frac{(\theta_{j,i}-1)\chi^2_{j,i}}{\chi^2_{j,i}}. \tag{12}$$

Then, we decompose the constraint in (12) into the following two constraints:

$$h^2_{j,i} p_{d,i} \geq (\theta_{j,i}-1)\chi^2_{j,i}, \tag{13}$$

$$h^2_{j,i}\sum_{s=1}^{d-1} p_{d,i} + B_i\sigma^2_{j,i} \leq \chi^2_{j,i}. \tag{14}$$

It is obvious that the constraint in (13) is still non-convex. To overcome this non-convexity, we apply the first-order Taylor series expansion to approximate the left side with a linear approximation [7] [8]. With this, the approximated convex form of (13) can be written as

$$h^2_{j,i} p_{d,i} \geq \left(\theta^{(t)}_{j,i} - 1\right){\chi_{j,i}^{(t)}}^2 + {\chi_{j,i}^{(t)}}^2\left(\theta_{j,i} - \theta^{(t)}_{j,i}\right) + 2\left(\theta^{(t)}_{j,i} - 1\right)\chi^{(t)}_{j,i}\left(\chi_{j,i} - {\chi_{j,i}}^{(t)}\right), \tag{15}$$

where $\chi^{(t)}_{j,i}$ and ${\theta_{j,i}}^{(t)}$ represent the approximations of $\chi_{j,i}$ and $\theta_{j,i}$ at the t^{th} iteration, respectively. Similarly, the non-convex right-hand side of the inequality in (14) is approximated with a linear term. With this approximation, the constraint in (14) can be rewritten as [28]

$${\chi^{(t)}}^2_{j,i} + 2\chi^{(t)}_{j,i}\left(\chi_{j,i} - \chi^{(t)}_{j,i}\right) \geq h^2_{j,i}\sum_{s=1}^{d-1} p_{d,i}. \tag{16}$$

By incorporating the slack variables in (11), a new constraint can be written as

$$B_i \rho_{j,i} \geq z_{i,j}. \tag{17}$$

Note that the constraint in (17) is still non-convex. To deal with the non-convexity issue, we introduce the following SOC definition:

Definition 1: For any $\{x, y\} \geq 0$, a constraint $xy \geq q$ can be cast as the following SOC constraint [29]:

$$x + y \geq ||[2\sqrt{q} \quad x - y]||. \tag{18}$$

In fact, Definition 1 can be justified by taking the square of both sides of (18) as

$$x^2 + y^2 + 2yx \geq 4q + x^2 + y^2 - 2yx.$$

Accordingly,

$$4yx \geq 4q.$$

This is, in fact, equivalent to the constraint $xy \geq q$. This provides the justification behind the Definition 1. ■

Based on this SOC definition, the constraint in (17) can be cast as the following convex SOC constraint:

$$B_i + \rho_{i,j} \geq ||[2\sqrt{z_{i,j}} \quad B_i - \rho_{i,j}]||. \tag{19}$$

With the above approximations, the SRM problem defined in OP_1 can be transformed into the following convex optimization problem:

$$\tilde{OP}_1 : \underset{\Lambda}{\text{maximize}} \quad \sum_{i=1}^{C}\sum_{j=1}^{K_i} z_{j,i} \tag{20a}$$

$$\text{subject to} \quad (10b), (10c), (10d), (7d), (14), (16), (19), \tag{20b}$$

where Λ includes all the optimization variables of $\tilde{OP}_1$, such that $\Lambda \equiv \{p_{j,i}, z_{j,i}, \chi_{j,i}, \theta_{j,i}, \rho_{j,i}\}_{i=1}^{K}$. It is worth mentioning that solving the optimization problem $\tilde{OP}_1$ requires appropriate initialization, i.e., $\Lambda^{(0)}$. These variables can be initialized by selecting a set of initial power allocation that satisfies the total power constraints in (10c), and then, evaluating the corresponding slack variables. With this iterative technique, the solution at the t^{th} iteration is considered as the intended solution if the difference between two sequential values is less than a pre-defined threshold, μ. The algorithm of solving the SRM problem is summarized in Algorithm 1.

Algorithm 1 SRM based resource allocation technique for a downlink MC-NOMA system with opportunistic bandwidth allocation

Step 1: **I**nitialization of the slack variables (i.e.,$\Lambda^{(0)}$).

Step 2: **R**epeat

1) Solve the optimization problem $\tilde{OP}_1$.
2) Update the slack variables.
3) Until the required accuracy is achieved.

Step 3: End of the Algorithm.

Note that the objective of the proposed SRM design is to maximize the overall sum-rate, which might introduce a fairness issue in terms of the achieved rate of users and sum-rate of clusters. However, this opportunistic bandwidth allocations can be further investigated to address the fairness issue between users and clusters.

B. Complexity Analysis of The Proposed Iterative Algorithm

It is obvious that a solution to the SRM optimization problem, OP_1, can be determined by solving the approximated optimization framework $\tilde{OP}_1$ iteratively. Therefore, the complexity of solving OP_1 can be defined by quantifying the complexity of the approximated $\tilde{OP}_1$. At each iteration, the SOC optimization framework, $\tilde{OP}_1$, is solved through the interior-point method [30]. The complexity associated with $\tilde{OP}_1$ can be defined with an upper-bounded of $\mathcal{O}(\mathcal{M}^2\mathcal{N})$ [29], where $\mathcal{M}$ and $\mathcal{N}$ represent the number of optimization variables and the dimensions of the optimization problem $\tilde{OP}_1$, respectively. The complexity of solving OP_1 is proportional to the number of the iterations, and it can be defined as $\mathcal{O}\big(\log(\frac{1}{\epsilon_0})\mathcal{M}^2\mathcal{N}\big)$, where ϵ_0 is the required accuracy [23].

IV. Simulation Results

In this section, we evaluate the performance of the proposed MC-NOMA system with opportunistic bandwidth allocation against that of the conventional scheme with equal bandwidth allocation. We consider a MC-NOMA system with ten users (i.e., $K = 10$) that are divided into five groups (i.e., $C = 5$). The users are uniformly distributed in a circle with radius of 20 meters. The noise variance and path loss exponent are set to be 10^{-6} W and 3, respectively. Furthermore, the available bandwidth is assumed to be 10^6 Hz, i.e., $B = 10^6$ Hz. Fig.2 confirms that the achieved sum-rate with opportunistic bandwidth allocation outperforms the conventional scheme with the equal bandwidth allocation. In particular, a two-fold performance enhancement is observed. This performance improvement can be explained, as most of the bandwidth is allocated to the sub-band with good channel condition, which has a direct impact on the achievable sum-rate. For example, in opportunistic bandwidth allocation at TX-SNR= 25 dB, the bandwidth allocated to the strongest sub-channel is $B_1 = 3.345 \times 10^5$ Hz. It is clear that the clusters with stronger users are allocated higher portions of the available bandwidth in the opportunistic design, which has a considerable impact on its overall performance.

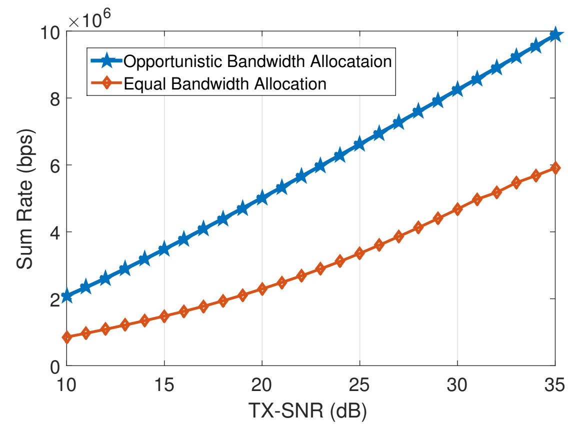

Fig. 2: Achieved sum-rate with different transmit signal-to-noise ratio (TX-SNR) levels.

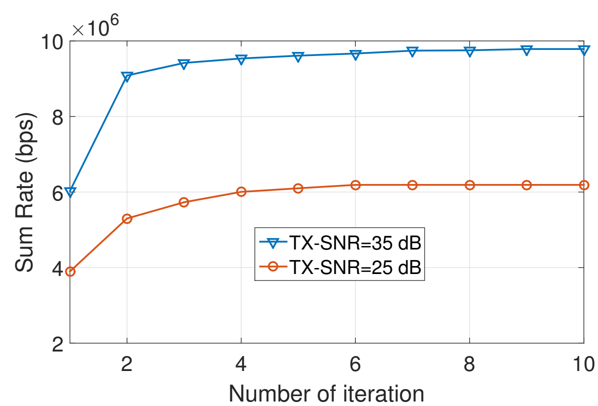

Fig. 3: The convergence of the proposed algorithm.

Furthermore, Fig. 3 shows that our approach to solve the SRM optimization problem converges to the solution within a few number of iterations.

V. Conclusion

In this letter, we proposed a SRM based resource allocation technique for a MC-NOMA system with opportunistic bandwidth allocation. Unlike the conventional scheme with equal bandwidth allocation, the allocated bandwidth for each subband is treated as a design variable along with the power allocation. We employed a SOC approach and iterative SCA algorithm to deal with the non-convexity of the SRM optimization problem. Simulation results confirmed that the proposed technique outperforms the equal bandwidth allocation scheme in terms of achieved sum-rate.

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