Energy Efficiency and Spectral Efficiency Tradeoff for Multicarrier NOMA Systems with User Fairness

Yan Zuo†, Xu Zhu*†, Yufei Jiang†, Zhongxiang Wei*, Haiyong Zeng†, Tong Wang†

* Department of Electrical Engineering and Electronics, The University of Liverpool, Liverpool, UK

† School of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen, China

Emails: zuoyan@stu.hit.edu.cn, xuzhu@ieee.org, jiangyufei@hit.edu.cn, hszwei@liverpool.ac.uk, zenghaiyong@stu.hit.edu.cn, tongwang@hit.edu.cn

***Abstract*—We propose a novel low-complexity resource allocation scheme to provide a tradeoff between energy efficiency (EE) and spectral efficiency (SE) for multicarrier non-orthogonal multiple access (NOMA) systems with the constraint of user fairness. The proposed optimization approach provides high degree of freedom, as the tradeoff of EE and SE can be optimal by assigning their corresponding weights. Also, a closed-form expression is derived for subchannel power allocation with user fairness, requiring no high-complexity search. A suboptimal power allocation approach is proposed on each subchannel for NOMA user pairing. Numerical results show that the proposed NOMA system provides higher EE and SE than the state-of-art methods, while requiring low complexity.**

I. Introduction

For the explosive growth of high-data-rate applications and services, non-orthogonal multiple access (NOMA) was proposed [1][2] to enhance spectral efficiency (SE). Multiple users can be multiplexed on the same subchannel and successive interference cancellation (SIC) is applied at the receiver to eliminate co-channel interference. Furthermore, its capabilities can be extended by combining the NOMA principle and subcarrier schemes. The system-level performance for downlink NOMA was investigated in [3] and the practical assumptions is investigated in [4]. Most previous work on NOMA has focused on power allocation to improve data rates. As transmit power increases, electromagnetic pollution and energy consuming become high. It is an inevitable trend to study green radio [5-10]. Besides, power-domain NOMA utilizes different power to distinguish users multiplexed on the same subchannel. Therefore, it is vital for NOMA systems to allocate power appropriately.

Up to now, there is much work on energy efficiency (EE) of NOMA systems. In [5], a novel method was proposed to balance between the data rate and power consumption in hybrid duplexing systems. In [6], EE optimization was studied for NOMA systems subject to the quality of service (QoS) requirement for each user. However, it assumed that all users transmit signals on over bandwidth, causing a high complexity for receiver. In [7], power-efficient resource allocation for multicarrier NOMA systems was studied. The subchannel assignment and power allocation to maximize the EE were studied in [8]. Energy and spectrum efficiency tradeoff for OFDMA was investigated in [9]. Afterwards, the relation of EE-SE has been studied in other systems, such as heterogeneous networks [10], the distributed antenna systems [11], orthogonal frequency division multiplexing (OFDM) [12][13]. In [14], EE and SE tradeoff problem in downlink NOMA systems was considered. However, it only studied two users in a single-carrier NOMA systems. In practical multicarrier system, power allocation and user scheduling are more complex.

The widely studied EE-optimal and SE-optimal problems purely consider the users in good channel conditions. User fairness should be taken into consideration as well. In [16], the authors investigated power allocation techniques to ensure fairness for the downlink users under instantaneous channel state information (CSI) and average CSI, respectively. In [17], the subchannel assignment and power allocation were jointly optimized to maximize sum rates while taking into consideration user fairness. In summary, there is no study which focuses on EE and SE tradeoff optimization problem in multicarrier NOMA systems considering user fairness.

However, EE and SE sometimes contradictory, as SE improves with the price of the decrease of the EE. In this paper, we study a multi-objective optimization problem in downlink multicarrier NOMA systems. Considering user fairness, we jointly optimize the SE and EE. The multi-objective optimization is suitable for different performance criteria. Since the joint problem is a mixed integer non-linear program, we solve the optimization problem in two steps: user scheduling and power allocation. A low-complexity suboptimal user scheduling scheme is proposed. Afterwards, an effective power allocation method is proposed. The main contributions are summarized as follows. We propose a multi-objective optimization approach for NOMA systems to provide a trade off by SE and EE, by assigning their corresponding weights. Also, considering user scheduling, we propose a subchannel and power allocation approach with a closed-solution, contributing to low complexity. A

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new low-complexity user scheduling is proposed by pairing NOMA user, avoiding high-complexity searching. Numerical results show that the proposed NOMA system provide better EE and SE performance than the previous method in [15], while providing low-complexity user scheduling and power allocation.

The rest of this paper is organized as follow. In section II, we describe the NOMA systems model and formulate the optimization problem. In section III, we optimize the problem from user scheduling and power allocation, respectively. Then, numerical simulation is presented in section IV. Finally, section V concludes the paper.

II. System model

In this section, we consider a downlink multicarrier NOMA systems. The total bandwidth *B* of the system is equally divided into *M* subbands, where the bandwidth of each subchannel is B_S. Multiple users are multiplexed on a subchannel. *K* user equipments (UEs) are deployed randomly in the coverage of base station (BS). The BS and UEs are equipped with a single antenna, respectively. In this paper, we first divide K UEs into two groups equally, corresponding to the users with higher channel gain are strong users while the ones with lower channel gain are weak users, which are denoted as $i \in \{0, ..., K/2-1\}$ and $j \in \{0, ..., K/2-1\}$, respectively.

A. System Model

According to the principle of NOMA, a single subchannel can be assigned *N* UEs. In order to achieve low complexity of SIC, we assume two UEs on the same subchannel at most, as in [15]. A superposition coded symbol is broadcasted by the BS on subchannel $m \in \{0, ..., M-1\}$.

$$S_m = \sqrt{a_m P_m} S_i + \sqrt{(1-a_m)P_m} S_j, \tag{1}$$

where S_i and S_j denote complex symbols of strong and weak users, respectively. P_m is the power allocated to subchannel *m*. a_m is the power allocation coefficient between strong user and weak user on subchannel *m*, with $0 \le a_m < \frac{1}{2}$. Specially, please note that $a_m = 0$ means that only one user is on the subchannel *m*.

Perfect knowledge of the CSI is available at the BS. Then the received signal at strong and weak UEs can be expressed as

$$y_{m,i} = \sqrt{a_m P_m} h_{m,i} S_i + \sqrt{(1-a_m)P_m} h_{m,i} S_j + n_{m,i}, \tag{2}$$

$$y_{m,j} = \sqrt{a_m P_m} h_{m,j} S_i + \sqrt{(1-a_m)P_m} h_{m,j} S_j + n_{m,j}, \tag{3}$$

where $n_{m,i}$ and $n_{m,j}$ denote the complex additive white Gaussian noise (AWGN) with zero mean and variance σ^2, $h_{m,i} = g_{m,i}(L(d)\ \xi)^{-1/2}$ denotes the CSI of user i on subchannel m, with $g_{m,i}$ being the Rayleigh fading coefficient, $L(d)$ being the path loss function between user and BS, ξ being the shadowing, $h_{m,j}$ denotes the CSI of user j on subchannel m. For simplicity, the channel to noise ratio (CNR) of user $k \in \{0, ..., K-1\}$ on subchannel m is defined as $H_{m,k} = |h_{m,k}|^2 \big/ \sigma^2$.

In downlink NOMA systems, it is assumed that the strong user can successfully decode the signal of weak user and there is no error propagation. Since the weak user treats the signal from strong user as noise, the achievable data rates of user i and user j on subchannel *m* can be formulated as

$$R_{m,i} = B_S \log_2(1 + \mathit{\Gamma} a_m P_m H_{m,i}), \tag{4}$$

$$R_{m,j} = B_S \log_2(1 + \mathit{\Gamma} \frac{(1-a_m)P_m H_{m,j}}{1 + \Gamma a_m P_m H_{m,j}}), \tag{5}$$

where $\mathit{\Gamma}$ is the loss of signal to interference plus noise ratio (SINR) that defines the gap between the channel capacity and a practical coding and modulation scheme. When $\mathit{\Gamma} = 1$ (0 dB), it is used to characterize Shannon capacity.

Then R_m denotes the sum data rates on subchannel m, which is given as

$$R_m = B_S[\log_2(1 + \mathit{\Gamma} a_m P_m H_{m,i}) + \log_2(\frac{1 + \mathit{\Gamma} P_m H_{m,j}}{1 + \mathit{\Gamma} a_m P_m H_{m,j}})]. \tag{6}$$

B. SE and EE

Generally, SE and EE for downlink transmission are defined as

$$\eta_{\mathrm{SE}} = \frac{\sum_{m=1}^{M} R_m}{B}, \tag{7}$$

$$\eta_{\mathrm{EE}} = \frac{\sum_{m=1}^{M} R_m}{B(\kappa P_T + P_C)}, \tag{8}$$

where κ is the drain efficiency of the power amplifier at the BS, P_T denotes the BS transmit power, P_C denotes the circuit power consumption, including the power consumption of the digital-to-analog converter, the frequency synthesizer, the mixer and so on.

In general, the BS needs power as much as possible to increase SE performance. However, with power increasing, EE gain may decrease.

C. Optimization Problem Formulation

Our objective is to maximize both SE and EE by effective users scheduling and power allocation among users. Generally, network has different communication demands in different scenarios. For example, it is more important to increase SE during peak hours. On the other hand, systems focus more on EE metric during the off-peak time. Hence, it is important to solve a multi-objective problem about resource allocation. Generally, it is solved by combing several competing problems into a single-objective problem. A priority between metrics is considered to find the optimal solution. What's more, we normalize the unit for EE and SE to combine them appropriately. Different from [18], NOMA systems focus more on power allocation. Therefore, a new metric can be defined as

$$\lambda_{\mathrm{EE-SE}} \triangleq \theta\eta_{\mathrm{EE}} + (1-\theta)\frac{\eta_{\mathrm{SE}}}{\kappa P_{\max} + P_C}, \tag{9}$$

where $P_{\max}$ denotes the maximum transmit power of BS, θ denotes the priority factor between η_{EE} and η_{SE} with respect to consumption power and capacity. Hence, the optimization problem can be formulated by

$$\begin{aligned} &\max \lambda_{\mathrm{EE-SE}} \\ &s.t. \\ &C1: P_T = \sum_{m=1}^{M} P_m \\ &C2: 0 \leq P_T \leq P_{\max}, \forall m \\ &C3: R_{m,j} \geq \Phi_j, \forall m, \end{aligned} \tag{10}$$

where $R_{m,j}$ denotes data rates of weak user j on sub-channel m, Φ_j denotes the weak user's data rate requirement. In this paper, we set Φ_j as data rate of weak user j in orthogonal frequency-devision multiple access (OFDMA) systems. Constraints $C1$ and $C2$ consider a limited transmit power in practical systems. In order to enhance SE performance of the system, more power will be allocated on strong users. Most recent work is based on QoS power allocation scheme, as in [10]. After satisfying the demand of weak users, the rest power is allocated on strong users to enhance the system capacity, while sacrificing user fairness. $C3$ is used to guarantee the data rates of the weak users in NOMA is higher than that in OFDMA. Obviously, the transformed non-probabilistic optimization problem is challenging to obtain the global optimal solution within polynomial time. In the following, we divide the optimal problem into two sub-problems: the user scheduling problem and the power allocation problem.

III. User Scheduling and Power Allocation Algorithm

A. User Scheduling

Different from the OFDMA systems, the user scheduling includes user pairing and subchannel allocation. Since it is difficult to find the optimal solution through exhaustive search, we propose a low-complexity user scheduling scheme.

In algorithm 1, we initialize a channel gain matrix $\mathbf{H}$ in which the entry $H_{m,k}$ denotes the CNR of user K on subchannel SC_m. UE_{all} is used to record the unallocated users of the system and SC_{all} denotes the available subchannels. At the first stage, we find the user with the maximum CNR value in $\mathbf{H}$ and allocate it on the corresponding subchannel as strong user, denoting as $SC_{\mathrm{strong}}(m)$. Each subchannel has only one strong users. At the second stage, we find the maximum CNR value from the rest users in UE_{all} and the user is multiplexed on the corresponding subchannel as weak user, denoting as $SC_{\mathrm{weak}}(m)$. This process terminates if UE_{all} is empty. The time complexity of exhaustive searching is exponential. However, the overall complexity of the proposed algorithm is $\mathcal{O}(M^2)$.

Algorithm 1 GROUPING

Construct an $M \times K$ channel gains $\mathbf{H}$ with (m,k) entry $H_{m,k}$.
Initialize the sets UE_{all} and SC_{all} to record the all users and sub-channels in the system.
Initialize the lists $SC_{\mathrm{strong}}(m)$, $SC_{\mathrm{weak}}(m)$ to record the users on SC_m.
while $UE_{\mathrm{all}} \neq \emptyset$ **do**
  Find the maximum value $H_{m,k}$ in $\mathbf{H}$.
  Assign the user i onto SC_m, then $UE_i \cup SC_{\mathrm{strong}}(m)$.
  $UE_{\mathrm{all}} = UE_{\mathrm{all}} \backslash UE_i$. Let the i th column's elements in $\mathbf{H}$ be zeros.
  $SC_{\mathrm{all}} = SC_{\mathrm{all}} \backslash SC_m$.
end while
Allocate the rest users onto $SC_{\mathrm{weak}}(m)$ as above.

B. Joint Power Allocation Scheme

Since the user pairing and subchannel allocation are given, we can improve the performance of NOMA systems by efficient power allocation. The optimal problem (10) can be decomposed into two layers to solve. In the inner layer, for a given transmission power $\mathbf{P}_T$, we can find the optimal subchannel power allocation while satisfying the fairness requirement. According to $C3$, we could get

$$a_m \leq \frac{\mathit{\Gamma} P_m H_{m,j} - V_m}{(V_m+1)\mathit{\Gamma} P_m H_{m,j}}, \tag{11}$$

where

$$V_m = \sqrt{1 + \mathit{\Gamma} P_T / M H_{m,j}} - 1. \tag{12}$$

It can be found that $\frac{dR_m}{da_m} > 0$ when $H_{m,i} > H_{m,j}$. Hence R_m strictly increases with a_m, the optimal solution to intra-subchannel power allocation is ${a_m}^* = \frac{\mathit{\Gamma} P_m H_{m,j} - V_m}{(V_m+1)\mathit{\Gamma} P_m H_{m,j}}$. As a_m has an upper bound, that is $\frac{1}{2}$, it is indicated that NOMA systems always have better performance, comparing to OFDMA systems.

Then the optimal inter-subchannel power allocation is given by using the Lagrangian function. We substitute (11) into the equation (6), and the corresponding Lagrangian function can be given as

$$\begin{aligned} &L(P_T, \lambda) \\ &= -B_s \sum_{m=1}^{M} \log_2(1 + V_m + \frac{H_{m,i}}{H_{m,j}}(\mathit{\Gamma} P_m H_{m,j} - V_m)) \\ &+ \lambda(\sum_{m=1}^{M} P_m - P_T), \end{aligned} \tag{13}$$

where λ is the Lagrange multiplier corresponding to the constraint $C1$. The optimal power allocation policy for sub-channel m can be derived as

$${P_m}^* = [u - A_m]^+, \forall m \in \{1, ..., M\}, \tag{14}$$

$$\sum_{m=1}^{M} {P_m}^* = P_T, \tag{15}$$

where

$$A_m = \frac{1+V_m}{H_{m,i}\varGamma} - \frac{V_m}{H_{m,j}\varGamma}, \qquad (16)$$

$[x]^+ = \max(0,x)$ and u is an intermediate variable.

In the outer layer, the bisection method is used to find the optimal P_T. $P_{\min}$ is the minimum required transmit power for the given user scheduling. In the inner layer, the Lagrangian function is used for power allocation across all subchannels. Therefore, the complexity of power allocation remains low with the increasing number of users. The process of power allocation is described as Algorithm 2.

Algorithm 2 Joint Optimal Allocation Algorithm

Initialize the transmit power ${P_T}^{(1)} = P_{\max}, {P_T}^{(2)} = P_{\min}$, the iteration index t=1, and the tolerance tol=0.0001.
For a given ${P_T}^{(1)}$, calculate $d_1 = \frac{d\lambda_{\mathrm{EE-SE}}}{dP_T}|_{P_T={P_T}^{(1)}}$.
if $d_1 \geq 0$ **then**
  Output ${P_T}^* = {P_T}^{(1)}$;
else
  For a given ${P_T}^{(2)}$, calculate $d_2 = \frac{d\lambda_{\mathrm{EE-SE}}}{dP_T}|_{P_T={P_T}^{(2)}}$.
end if
if $d_2 \leq 0$ **then**
  Output ${P_T}^* = {P_T}^{(2)}$;
else
  $a = {P_T}^{(2)}, b = {P_T}^{(1)}, f(a) = d_2, f(b) = d_1$
  c $=\frac{a+b}{2}, f(c) = \frac{d\lambda_{\mathrm{EE-SE}}}{dP_T}|_{P_T=c}$.
  while $|f(c)| \geq tol$ **do**
    if $f(a) * f(c) > 0$ **then**
      a= c, $f(a) = f(c)$;
    else
      $b = c, f(b) = f(c)$;
    end if
    $t = t+1$;
    $c = \frac{a+b}{2}, f(c) = \frac{d\lambda_{\mathrm{EE-SE}}}{dP_T}|_{P_T=c}$.
  end while
end if
Output current ${P_T}^*, t$.

IV. Simulation Results

In this section, numerical results are presented to evaluate the performance of the proposed resource allocation algorithms for NOMA systems. In the simulations, a single cell with 10 users being distributed randomly is considered. The radius of the cell is 500 meters and the minimum distance between BS and users is 50 meters. The wireless communication channel is consisted of independent Rayleigh Channel, which is modeled by Jake's flat fading channel. The total bandwidth $B = 5$ MHz. The AWGN power spectral density of noise is -174 dBm/Hz. The circuit power consumption is $P_C = 20$ dBm and the BS maximum transmit power is $P_{\max} = 35$ dBm. The power amplifier coefficient is set as $\kappa = 1$. In NOMA systems, the modified Hata urban propagation model is considered, which is expressed as $L(d) = 128 + 37.6\log(d)$. The shadowing follows a log-normal distribution with zero mean and variance of eight. For the sake of simplicity, we set $\varGamma = 1$.

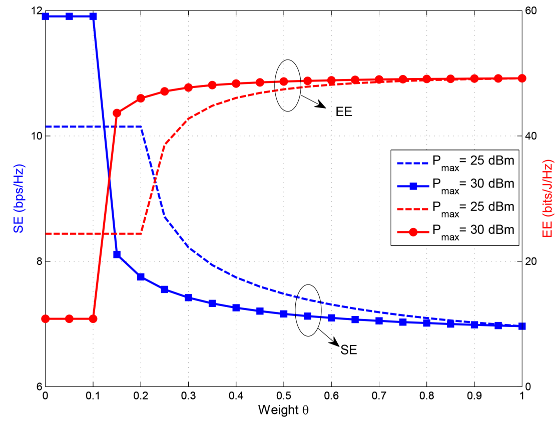

Fig. 1. EE and SE versus weight θ for different $P_{\max}$

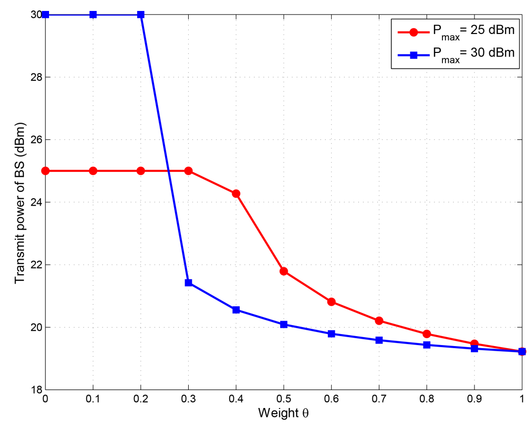

Fig. 2. Transmit power of BS versus weight θ

Fig.1 illustrates the SE and EE performance versus priority weight with different maximum transmit power of BS. When the transmit power is large, such as $P_{\max} = 30$ dBm, the BS works out an optimal transmit power according to the priority weight θ. With the priority weight increasing, the NOMA systems give priority to the EE performance. By choosing a priority weight, we can make a tradeoff between SE and EE for a practical scenario.

Fig.2 shows the relation between transmit power of BS and weight θ. When weight $\theta \to 0$, the BS consumes overall transmit power to enhance SE gain. While weight $\theta \to 1$, EE is a more important metric. It is showed that the less power is consumed for network, which is suitable for green communications.

Fig.3 shows SE performance of total users and weak users versus transmit power. Equal power allocation across subchannel (EPAAS) scheme in [15] guarantees that weak

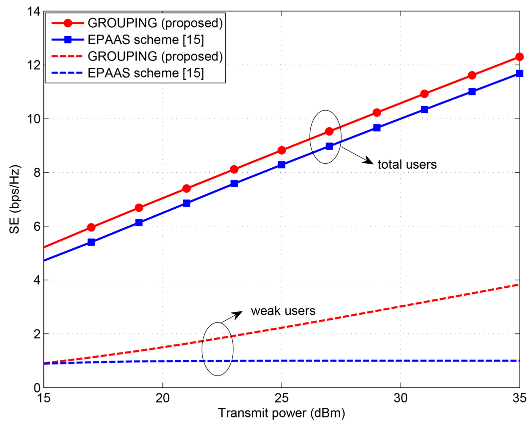

Fig. 3. SE performance versus transmit power

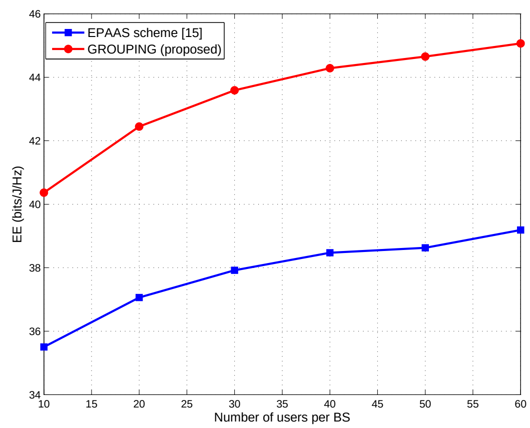

Fig. 4. EE performance versus the number of users

users could satisfy the same minimum data rate requirement. We can see that weak users improve their data rates, without deteriorating SE performance.

Fig.4 shows EE performance versus the number of users. The proposed algorithm have better EE performance than EPAAS. This is because the system allocates power to weak users according the requirement of communication.

V. Conclusion

In this paper, an EE-SE tradeoff framework has been proposed, where different communication demand of the cell-edge user is considered. According to different scenarios, we can select the priority weight to jointly optimize SE and EE. The multi-objective problem can be converted into a quasi-concave problem. Then a low-complexity user scheduling combined with a dual-layer power allocation method are proposed, where in the inner layer intra-subchannel power allocation is solved using Lagrangian multiplier method, and in the outer layer an iterative method based on the bisection method is proposed. Numerical results show the energy efficiency and spectral efficiency can be improved in our proposed method while the complexity is much lower.

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