

# Power Allocation for Multi-Cell Non-Orthogonal Multiple Access Networks: Energy Efficiency vs. Throughput vs. Power Consumption

Syllas R. C. Magalhães, Suzan Bayhan, Geert Heijenk  
University of Twente, The Netherlands  
{s.magalhaes, s.bayhan, geert.heijenk}@utwente.nl

**Abstract**—The pressing need for more energy-efficient networks requires understanding the trade-offs maintained by emerging technologies that are expected to help serve an increasing number of connected devices and meet their rate requirements. While spectral efficiency is typically a key performance indicator, hence used for optimal resource allocation, energy efficiency and power consumption of a wireless network should also be considered while deciding on the potential adoption of a new technology. In this paper, we focus on non-orthogonal multiple access (NOMA) as it is considered as a candidate radio access scheme due to its promise to improve spectral efficiency. With a goal of understanding whether joint transmission offers benefits over conventional NOMA, we investigate the performance of joint-transmission NOMA and NOMA considering three objectives: throughput maximization (SumRate), energy efficiency maximization (EE), and power minimization (minP). Different from the literature, we incorporate a power consumption model that accounts for the overhead introduced by successive interference cancellation that is necessary to distinguish the intended signal of a NOMA receiver from the interfering signals aimed for other users in the same cluster. After formulating the optimal power allocation problems, we present our solution steps to make the original problems convex for solving them optimally. Our numerical analysis shows that, for the studied two-cell scenario, joint-transmission offers a benefit only in terms of finding a feasible power allocation while NOMA fails in more cases irrespective of the considered objective. Additionally, our investigation of trade-offs between the investigated problems shows orders of magnitude difference in energy efficiency and throughput for small variations in power consumption.

## I. INTRODUCTION

Due to the growing concerns on the energy consumption of communication networks, it has become essential to investigate the trade-offs, such as throughput vs. energy efficiency, offered by the emerging technologies before their wide adoption. In this context, one of the promising technologies is non-orthogonal multiple access (NOMA), which can provide significant improvement in spectral efficiency (SE) over orthogonal multiple access [1]. NOMA enables a transmitter to send its traffic to multiple receivers simultaneously through the same time-frequency resource block(s) by leveraging superposition coding [2]. Consequently, NOMA receivers need to extract the signals intended for themselves by applying *successive interference cancellation* (SIC). However, signals for the users in the same NOMA cluster with higher decoding order are treated as interference, which deteriorates the channel capacity. Particularly, cell-edge users will experience a higher level of interference as they typically have lower decoding orders [3].

In multi-cell scenarios, interference at the cell-edge users can be more severe due to co-channel transmissions in

neighbouring cells. A common approach to mitigate inter-cell interference is to use coordinated multi-point (CoMP) approach [4]. More specifically, joint transmission (JT)-CoMP can both reduce interference and improve spectral efficiency, since it transforms unwanted inter-cell interference into useful signal power [5]. However, the resulting energy efficiency of JT-CoMP NOMA (JTCN) systems has not been investigated thoroughly. Moreover, prior work overlooks the SIC power consumption at the NOMA receivers and typically accounts for only transmission power and transmitter's circuit power. Our recent work [6] suggests that accurately modelling power consumption plays a key role in the achieved network energy efficiency, especially for scenarios where the receivers' data rate requirement is low. In these regimes, the use of an oversimplified power consumption model (PCM) in power allocation might lead to considerable loss in energy efficiency and throughput, while more accurate models accounting for receiver side power consumption improve energy efficiency.

To understand the trade-offs maintained among key performance indicators, we investigate here the impact of different optimization approaches on the achieved throughput, energy efficiency, and power consumption in JTCN and NOMA. Our goal is to quantify the gains (and losses) in various key performance indicators achieved by an energy-efficiency maximization problem in comparison to an approach aiming at throughput maximization or power consumption minimization. Concisely, we aim at addressing the following research question: *how does the optimization objective affect the achieved throughput, energy efficiency, and power consumption in case of JTCN and NOMA considering a PCM that accounts for power consumption due to SIC at NOMA receivers?* While addressing this question, our contributions are as follows:

- We formulate and solve three power allocation optimization problems considering energy-efficiency maximization, throughput-maximization, and network power-minimization objectives for a two-cell downlink JTCN with minimum user rate requirements and SIC constraints. Different from prior work, we adopt a power consumption model that accounts for overhead due to SIC at the NOMA receivers.
- We assess the performance of the introduced power allocation problems with varying rate requirements of the users considering network energy efficiency, network throughput, power consumption, and Jain's fairness index. Additionally, to develop insights on the trade-offs among throughput, energy efficiency, and power consumption, we investigate the gains (or losses) of optimizing for energy efficiency over optimizing for throughput or for power.

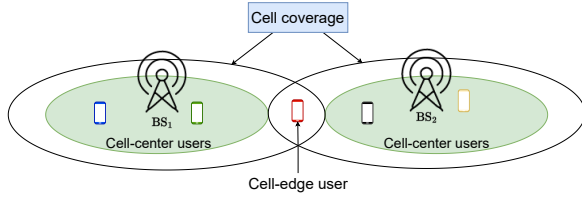


Fig. 1. A two-cell NOMA scenario where a cell-edge user can be served jointly by both BSs if joint-transmission mode is activated.

- We conclude that under favourable channel conditions, JTCN does not bring throughput or energy efficiency benefits over *dynamic cell selection (DCS)-CoMP* [7]. In other words, a simple cell selection strategy suffices to deliver the same throughput as JTCN, which requires tight interworking of multiple BSs for serving cell-edge users.

## II. RELATED WORK

Some studies such as [8] compare JTCN with JT-CoMP OMA and show that NOMA improves spectral efficiency in comparison to OMA. However, our key question is whether the joint transmission is beneficial to NOMA networks, which is not addressed in these studies. Reference [9] shows that joint transmission can improve energy efficiency compared to a power control algorithm [10] in a multi-cell NOMA setting. However, the goal of the algorithm devised in [10] is to minimize the total power consumption instead of maximizing energy efficiency. Despite appearing similar to an energy-efficiency maximization objective, an algorithm with a power consumption minimization objective might prefer an operation point with lower energy efficiency compared to the latter. In [11], the authors show that dynamic cell selection (DCS)-NOMA outperforms JTCN. However, they assume in JTCN that the cell-edge users that are collectively served by multiple BSs are allocated the same power from all coordinated BSs. Consequently, this constraint leads to a low performance for JTCN. Different from [11], we model a generic JTCN scenario in which DCS-NOMA is a special case. Moreover, none of the existing works reflects the power consumption cost emerging due to SIC that is a key enabler of NOMA. With increasing NOMA cluster size where the receivers with the highest decoding order have to perform many SIC layers, the gap between the achieved energy efficiency and the modelled expected energy efficiency might differ considerably. Therefore, different from these studies, we consider a more elaborate power consumption model introduced in our recent work [6] to compare JTCN and NOMA in terms of their energy efficiency. In this paper, we extend the work in [6] by considering different optimization objectives.

## III. SYSTEM MODEL

We consider a downlink multiuser NOMA system as in Fig. 1, which consists of  $N_{BS}$  cells. Each cell contains a base station (BS)  $BS_b$  located at the center of the cell serving  $J_b$  users. We distinguish between cell-edge and cell-center users based on their distance to the corresponding BS. We assume a single cell-edge user in the coverage area of all BSs and an equal number of cell-center users in the coverage area of each BS.

Let us denote by  $u_{i,b}$  the  $i^{\text{th}}$  user served by  $BS_b$  where  $1 \leq i \leq J_b$  and  $1 \leq b \leq N_{BS}$ . Moreover, let us assume universal frequency reuse with a single NOMA cluster in each cell. Each BS serves its users by sending a superposed signal containing the signals intended for them using  $\omega$  frequency resource blocks, each with a bandwidth of  $B$  Hz. To obtain its signal, each user performs SIC to cancel the signals for users with lower SIC order. We assume that the user's indices are sorted according to the descending order of their channel-to-noise ratio (CNR) denoted by  $\tilde{h}_{i,b}$ :  $\tilde{h}_{i,b} \geq \tilde{h}_{i+1,b}$  and the cell-edge user has the worst channel  $\tilde{h}_{J_b,b}$ . Then, we assume that the SIC decoding order follows the descending order of the user's indices. We can calculate  $\tilde{h}_{i,b}$  as follows:  $\tilde{h}_{i,b} = \frac{|h_{i,b}|^2}{BN_0}$  where  $h_{i,b}$  is the flat Rayleigh fading channel from  $BS_b$  to user  $u_{i,b}$  over the bandwidth  $B$  and  $N_0$  is the noise power spectral density. Similarly, we calculate  $\tilde{h}_{i,b,b'}$ , which is the CNR between  $BS_{b'}$  and  $u_{i,b}$ , using  $h_{i,b,b'}$ , the flat Rayleigh fading channel from  $BS_{b'}$  to  $u_{i,b}$ . Moreover, we denote by  $p_{i,b}$  the power allocated by  $BS_b$  to  $u_{i,b}$ .

At the beginning of a time slot, a central entity determines the power allocation for all NOMA clusters to ensure that each user maintains a minimum data rate specified by its application ( $R_{i,b}^{\min}$  bps for  $u_{i,b}$ ). For JTCN, the cell-edge user is served by all BSs, i.e.,  $u_{J_b,b}$  refers to the same user regardless of  $b$ . Consequently, the data rate requirement  $R_{J_b,b}^{\min}$  has to be jointly met by all cooperating BSs. Next, we present the considered JTCN and NOMA scenarios and derive the corresponding achievable downlink data rates.

### A. Conventional NOMA

In this case (shortly referred to as NOMA), the cell-edge user is served by only one of the BSs, i.e., each user is part of a single NOMA cluster. For simplicity, we assume that the edge user is always connected to the first BS, i.e.,  $p_{J_b,b} = 0$  for all  $b \neq 1$ . Then, the achievable downlink data rate (using the Shannon capacity) for  $u_{i,b}$  is calculated as in [6]:

$$R_{i,b}^{\text{NOMA}} = \omega B \log_2 \left( 1 + \frac{p_{i,b} \tilde{h}_{i,b}}{\sum_{b'=1, j=1}^{N_{BS}, J_{b'}} p_{j,b'} \tilde{h}_{i,b,b'} + \sum_{j=1}^{i-1} p_{j,b} \tilde{h}_{i,b} + \omega} \right) \quad (1)$$

where the first term in the denominator represents the inter-cell interference and the second term represents the intra-cluster interference, hence, the interference of the remaining superposed signals after SIC. Therefore,  $u_{J_b,b}$  experiences full intra-cluster interference, while  $u_{1,b}$  cancels all the superposed signals first, i.e., does not experience intra-cluster interference.

### B. Joint Transmission CoMP NOMA (JTCN)

In the JTCN scheme, unlike conventional NOMA, multiple BSs can coordinate to simultaneously transmit the same data to a cell-edge user (also referred to as *CoMP user*). In this case, DCS-NOMA operation mode is also possible; only one of the BSs is selected for transmission to the CoMP user, i.e., power from one BS is zero and the other is positive. DCS-NOMA is similar to conventional NOMA, but the BS serving the edge user is dynamically selected. As in NOMA,

the signals transmitted by other BSs are treated as interference at cell-center users. However, as the CoMP user belongs to all NOMA clusters, this cell-edge user experiences only intra-cluster interference. Hence, we derive the data rate for cell-center users and cell-edge user separately. For a non-CoMP user  $u_{i,b}$ , we calculate  $R_{i,b}^{\text{JTCN}}$  similar to (1) as follows:

$$R_{i,b}^{\text{JTCN}} = \omega B \log_2 \left( 1 + \frac{p_{i,b} \tilde{h}_{i,b}}{\sum_{b'=1, b' \neq b}^{N_{BS}} \sum_{j=1}^{J_{b'}} p_{j,b'} \tilde{h}_{i,b,b'} + \sum_{j=1}^{i-1} p_{j,b} \tilde{h}_{i,b} + \omega} \right). \quad (2)$$

For the CoMP user, useful power is the sum of the power received from all BSs. Hence,  $R^{\text{JTCN}}$  is expressed as:

$$R^{\text{JTCN}} = \omega B \log_2 \left( 1 + \frac{\sum_{b=1}^{N_{BS}} p_{J_b,b} \tilde{h}_{J_b,b}}{\sum_{b=1}^{N_{BS}} \sum_{j=1}^{J_b-1} p_{j,b} \tilde{h}_{J_b,b} + \omega} \right). \quad (3)$$

#### IV. POWER OPTIMIZATION PROBLEMS

This section presents three power allocation approaches with objectives of power minimization (minP), sum-rate maximization (SumRate), and energy-efficiency maximization (EE). For each problem, we also describe the solution approach.

##### A. Power minimization problem (minP)

In this case, the goal is to find the minimum amount of power necessary to meet the data rate requirements while guaranteeing successful SIC. To compute power consumption, we use the model in [6] which also accounts for the SIC overhead and is expressed as:

$$P(\mathbf{p}) = \sum_{b=1}^{N_{BS}} \left( P_b^{\text{fix}} + \sum_{i=1}^{J_b} ((1 + \rho) p_{i,b} + (J_b - i + 1) \kappa) \right) \quad (4)$$

where  $\rho$  is a positive constant which accounts for the BS-related power-dependent signal processing power expenditure and  $\kappa$  is the average power consumption per SIC layer. The power minimization problem is formally defined as follows:

$$P_{\min P} : \min_{\mathbf{p}} P(\mathbf{p}) \quad (5)$$

subject to:

$$R_{i,b}^S \geq R_{i,b}^{\min}, \quad b = 1, \dots, N_{BS}, \quad i = 1, \dots, J_b - 1 \quad (6)$$

$$R^S \geq R^{\min} \quad (7)$$

$$R_{i,b}^S \geq R_{k,b}^{\min}, \quad b = 1, \dots, N_{BS}, \quad i = 1, \dots, J_b - 1, \forall k > i \quad (8)$$

$$\sum_{i=1}^{J_b} p_{i,b} \leq P_{\max}, \quad b = 1, \dots, N_{BS} \quad (9)$$

$$p_{i,b} \geq 0, \quad i = 1, \dots, J_b, \quad b = 1, \dots, N_{BS} \quad (10)$$

where (6) and (7) are the data rate requirements for cell-center users and cell-edge user, respectively. Const. (8) is the SIC constraint and (9) and (10) are, respectively, the maximum power per BS and non-negative power constraints. In (8),

$R_{i,b,k}^S$  is the data rate for  $u_{i,b}$  to decode  $u_{k,b}$ 's signal:

$$R_{i,b,k}^S = \omega B \log_2 \left( 1 + \frac{p_{k,b} \tilde{h}_{i,b}}{\sum_{b'=1, b' \neq b}^{N_{BS}} \sum_{j=1}^{J_{b'}} p_{j,b'} \tilde{h}_{i,b,b'} + \sum_{j=1}^{k-1} p_{j,b} \tilde{h}_{i,b} + \omega} \right).$$

If condition (8) holds, user  $i$  can correctly decode the signal intended for user  $k$  in the user  $k$  requested data rate so that reconstruction of the signal is possible during SIC. Using the same notation, the rate requirement constraints can be seen as the case where  $i = k$ , i.e.,  $R_{i,b} = R_{i,b,i}$ .

The objective function of  $P_{\min P}$  is affine, hence convex. The same holds for (9) and (10). However, the data rate-related constraints are non-convex functions, which prevent us to solve the problem using ordinary convex programming algorithms. To make them convex, we first convert the SIC constraints into

affine constraints. For that, let us first define  $\gamma_{k,b}^{\min} = \frac{R_{k,b}^{\min}}{2 \omega B} - 1$ , we can then manipulate (8) to obtain  $2 \frac{R_{i,b,k}^S}{\omega B} - 1 \geq \gamma_{k,b}^{\min}$ , i.e.,

$$\frac{p_{k,b} \tilde{h}_{i,b}}{\sum_{b'=1, b' \neq b}^{N_{BS}} \sum_{j=1}^{J_{b'}} p_{j,b'} \tilde{h}_{i,b,b'} + \sum_{j=1}^{k-1} p_{j,b} \tilde{h}_{i,b} + \omega} \geq \gamma_{k,b}^{\min}, \quad \text{therefore,} \quad (11)$$

$$p_{k,b} \tilde{h}_{i,b} - \gamma_{k,b}^{\min} \left( \sum_{b'=1, b' \neq b}^{N_{BS}} \sum_{j=1}^{J_{b'}} p_{j,b'} \tilde{h}_{i,b,b'} + \sum_{j=1}^{k-1} p_{j,b} \tilde{h}_{i,b} + \omega \right) \geq 0.$$

We follow the same procedure to convert the data rate requirement expressions. This is equivalent to setting  $k = i$  in (11). We remove  $R_{i,b,J_b}^{\text{JTCN}} \geq R_{i,b}^{\min}$  to allow convergence to DCS-NOMA. However, since  $u_{J_b,b}$  has the worst-channel in all clusters, it is highly likely that this constraint is met, and we only check after optimization.

##### B. Sum-rate maximization problem (SumRate)

This problem is formulated as follows:

$$P_{\text{SumRate}} : \max_{\mathbf{p}} \left( R^S + \sum_{b=1}^{N_{BS}} \sum_{i=1}^{J_b-1} R_{i,b}^S \right) \quad (12)$$

subject to: (6)-(10).

Different from  $P_{\min P}$ , the objective function in (12) is a non-concave function of the allocated power. This requires some additional steps in the solution of the problem to make it solvable through ordinary convex programming algorithms. To solve  $P_{\text{SumRate}}$ , we follow a similar approach described in [6], [12]. The first step is to convert the data rate expression into a concave function. We first introduce the following lower bound on the system data rate:

$$\log_2(1 + \gamma_{i,b}) \geq a_{i,b} \log_2(\gamma_{i,b}) + c_{i,b}, \quad (13)$$

where  $\gamma_{i,b} > 0$  represents the signal-to-interference-noise ratio

**Algorithm 1: Sum-rate optimization (SumRate)**


---

```

1: if  $P_{\min P}$  is feasible then
2:    $\epsilon > 0$ ;  $l = 0$ ; select  $\mathbf{p}^{(0)} = \mathbf{p}^*$  (solution of  $P_{\min P}$ )
3:   while  $|\text{EE}(\mathbf{p}^{(l+1)}) - \text{EE}(\mathbf{p}^{(l)})| > \epsilon$  do
4:      $l = l + 1$ ;
5:     Find  $\{a_{i,b}^{(l)}, c_{i,b}^{(l)}, c_b^{(1)(l)}\}_{\forall i, \forall b}$ , using (14), (15), (18)
6:     Find  $\mathbf{q}^{(l)}$  for concave version of  $P_{\text{SumRate}}$ 
7:      $\mathbf{p}^{(l)} = 2^{\mathbf{q}^{(l)}}$ ;
8: return  $\mathbf{p}^{(l)}$ 
    
```

---

(SINR) in  $R_{i,b}^S$  and  $\gamma_{i,b}^0 > 0$ , while  $a_{i,b}$  and  $c_{i,b}$  are:

$$a_{i,b} = \gamma_{i,b}^0 / (1 + \gamma_{i,b}^0) \quad \text{and} \quad (14)$$

$$c_{i,b} = \log_2(1 + \gamma_{i,b}^0) - \gamma_{i,b}^0 \log_2(\gamma_{i,b}^0) / (1 + \gamma_{i,b}^0). \quad (15)$$

Then, we introduce the variable substitution  $p_{i,b} = 2^{q_{i,b}}$ , which allows us to lower bound  $R_{i,b}^S$  as follows:

$$\begin{aligned}
 R_{i,b}^S &\geq a_{i,b} \omega B (\log_2(\tilde{h}_{i,b}) + q_{i,b}) + c_{i,b} \omega B \\
 &\quad - a_{i,b} \omega B \log_2 \left( \sum_{\substack{b'=1 \\ b' \neq b}}^{N_{BS}} \sum_{j=1}^{J_{b'}} 2^{q_{j,b'}} \tilde{h}_{i,b,b'} + \sum_{j=1}^{i-1} 2^{q_{j,b}} \tilde{h}_{i,b} + \omega \right). \quad (16)
 \end{aligned}$$

This procedure can be used to make (1) and (2) convex. For (3), this manipulation does not suffice due to the summation in the numerator. To make (3) concave, we use Lemma 4.2 from [12] in addition to the presented lower bounds to obtain:

$$\begin{aligned}
 R^S &\geq a_{i,b} \omega B \sum_{b'=1}^{N_{BS}} c_{b'}^{(1)} \left( q_{J_{b,b'}} + \log_2 \left( \frac{\tilde{h}_{J_{b,b'}}}{c_{b'}^{(1)}} \right) \right) + c_{i,b} \omega B \\
 &\quad - a_{i,b} \omega B \log_2 \left( \sum_{b'=1}^{N_{BS}} \sum_{j=1}^{J_{b'}-1} 2^{q_{j,b'}} \tilde{h}_{J_{b,b,b'}} + \omega \right) \quad (17)
 \end{aligned}$$

where  $\sum_{b'=1}^{N_{BS}} c_{b'}^{(1)} = 1$  and the above-presented lower bounds are tight with equality for  $\gamma_{i,b} = \gamma_{i,b}^0$  in (14) and (15), and

$$c_{b'}^{(1)} = \frac{2^{q_{J_{b,b'}}} \tilde{h}_{J_{b,b'}}}{\sum_{b'=1}^{N_{BS}} 2^{q_{J_{b,b'}}} \tilde{h}_{J_{b,b'}}}, \quad \forall b' \quad (18)$$

in (17). We then solve  $P_{\text{SumRate}}$  iteratively using  $P_{\min P}$  as the initial solution and updating (14), (15) and (18) with the solution of the previous iteration (as summarized in Alg. 1).

### C. Energy efficiency maximization problem (EE)

To accurately account for the SIC overhead in terms of power consumption at the receivers, we adopt the power consumption model used in (4). This problem is therefore

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Cell radius	600 m
Max. BS transmit power ( $P_{\max}$ )	43 dBm
Noise spectral density ( $N_0$ )	-139 dBm/Hz
Bandwidth of a RB ( $B$ )	180 kHz
Path loss model	Macrocell pathloss [13]
# of users per NOMA cluster	2 or 3
# of RBs per NOMA cluster ( $\omega$ )	100
BS circuit power ( $P^{\text{fix}}$ )	30 dBm [11]
Mean power/SIC layer ( $\kappa$ )	0.5 Watts [6]
Signal processing overhead ( $\rho$ )	0.1

equivalent to the one investigated in [6] and is defined as:

$$P_{\text{EE}} : \max_{\mathbf{p}} \left( \frac{R^S + \sum_{b=1}^{N_{BS}} \sum_{i=1}^{J_b-1} R_{i,b}^S}{P(\mathbf{p})} \right) \quad (19)$$

subject to: (6)-(10).

Different from [6], we introduce SIC constraints in (8) to ensure that SIC is performed successfully. We follow the same solution approach in [6] that leverages Dinkelbach's algorithm.

## V. PERFORMANCE ANALYSIS

This section presents a performance analysis of the formulated power allocation approaches for JTCN and NOMA. We resort to Monte Carlo simulations and analyze the performance using the following performance metrics.

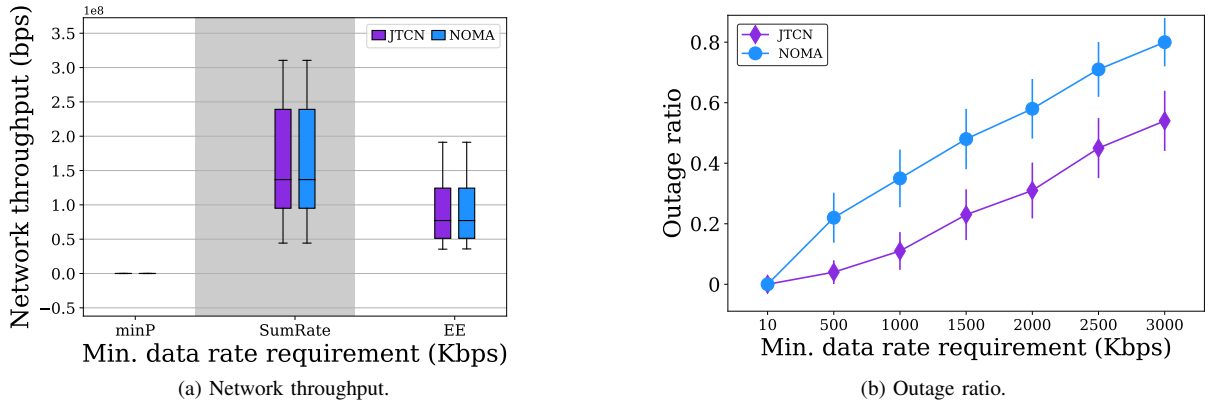
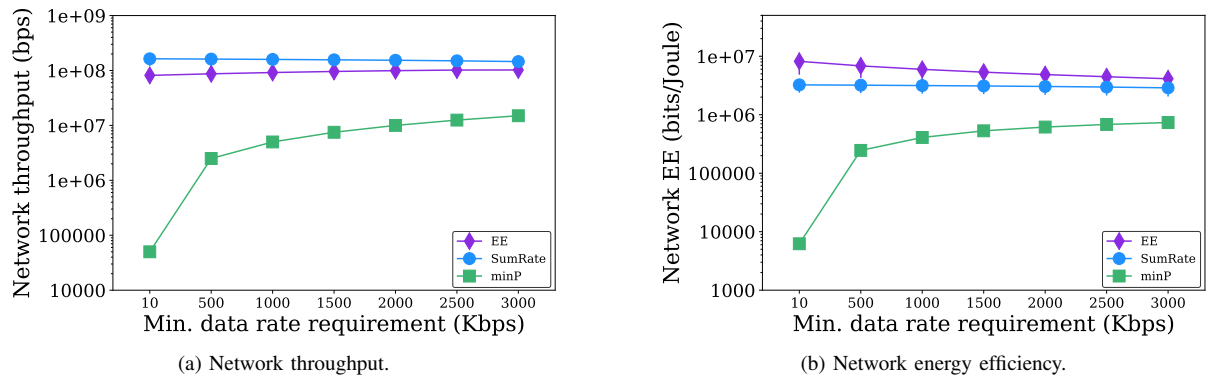
- *Network power consumption [Watt]*: We define the network power consumption  $P(\mathbf{p})$  as in (4).
- *Network energy efficiency [bits/Joule]*: We define the network energy efficiency as the ratio between the sum of the achievable data rate of all users in the network and total consumed power in the network, resulting in:

$$EE = \frac{R^S + \sum_{b=1}^{N_{BS}} \sum_{i=1}^{J_b-1} R_{i,b}^S}{P(\mathbf{p})}.$$

- *Network throughput [bps]*: The throughput is defined as the sum of the achievable data rate of all users in the network and calculated as:  $R^S + \sum_{b=1}^{N_{BS}} \sum_{i=1}^{J_b-1} R_{i,b}^S$ .
- *Outage ratio*: When  $P_{\min}$  is infeasible, i.e., there exists at least one user whose minimum rate requirement cannot be met or SIC is not possible with the available power, we refer to this case as *outage*. Outage ratio is the fraction of all runs with outage.
- *Jain's fairness index*: To measure the difference among the throughput achieved by all receivers, we compute Jain's fairness index considering users' throughput [14].

We report the statistics of 100 runs with 95% confidence intervals. Moreover, we assume two BSs being 1 km apart and cell-center users are in a radius of 400 m around their serving BS. Table I lists the key parameters of the simulations.

To understand whether JTCN improves throughput compared to NOMA, we analyze these schemes for  $R^{\min} =$


 Fig. 2. Comparison of JTCN and NOMA under  $P_{\min P}$ ,  $P_{EE}$ , and  $P_{\text{SumRate}}$ .

 Fig. 3. Comparison of JTCN and NOMA under increasing  $R^{\min}$  for all problems.

1.5 Mbps. As Fig. 2a shows, JTCN and NOMA perform similarly in terms of network throughput irrespective of the optimization objective. As expected, the highest throughput is achieved by SumRate and the lowest by minP. To investigate further, we limit the sample space and consider only scenarios where both JTCN and NOMA find a feasible power allocation and the first BS serves the cell-edge user in JTCN. In these scenarios, we observe that NOMA and JTCN performance are equal. This result suggests that under favourable propagation conditions where the cell-edge user is associated with the BS that offers a better channel quality, JTCN's optimal operation mode for network throughput maximization is *dynamic cell selection (DCS)-CoMP* [7]. Further inspection reveals that power allocation for JTCN is the same as NOMA power allocation. Despite not offering throughput improvement, JTCN can still be beneficial as it significantly outperforms NOMA in terms of outage ratio, as Fig. 2b shows. With increasing  $R_{\min}$ , finding a feasible power allocation becomes more challenging for both schemes. However, NOMA leads to higher outage due to the necessity of assigning the edge user to a cluster prior to power optimization while JTCN introduces an additional degree of freedom, i.e., connecting to the best BS. In the rest of the paper, we focus on JTCN due to its outage ratio.

Now, let us investigate how network throughput and energy efficiency are affected by the optimization objective. From Fig. 3a, we observe that, as expected,  $P_{\min P}$  provides the lowest throughput, since it will only guarantee the lowest rate  $R^{\min}$  that is asserted by the user's application. Rates higher than

this minimum rate will increase the objective function's value, thereby being regarded as unfavourable. When it comes to network energy efficiency in Fig. 3b,  $P_{\min P}$  is also the least energy-efficient scheme, which points to the fact that power consumption minimization objective may not lead to the highest energy-efficiency regime. Considering  $P_{EE}$  and  $P_{\text{SumRate}}$ , the throughput and energy efficiency gap between these schemes and  $P_{\min P}$  decreases with increasing  $R^{\min}$ . This implies that when the rate requirements are low such as in cases of low-rate IoT scenarios, the choice of the objective should be done more cautiously according to the key performance indicators. For example, for cases where a user's satisfaction function does not monotonically increase with increasing throughput but is rather capped,  $P_{\min P}$  can provide a better solution with the lowest energy consumption.

To understand the trade-offs better between optimizing for one objective over another, Fig. 4 illustrates the gains and losses (represented as negative gains) in terms of energy efficiency, throughput, and power consumption. We define the gain as the ratio of performance achieved by EE to the performance of SumRate (or of minP) considering the metric of interest. For better visualization, we report the gains in decibels. Fig. 4a suggests that a throughput loss of  $\sim 2\times$  (3 dB) can lead to  $4\times$  (6 dB) lower power consumption on average when  $R^{\min} = 10$  Kbps. The gain in energy efficiency as well as loss in throughput and power consumption decreases with increasing  $R^{\min}$ . However, we observe still up to  $1.35\times$  gain in energy efficiency and  $1.6\times$  lower power consumption achieved

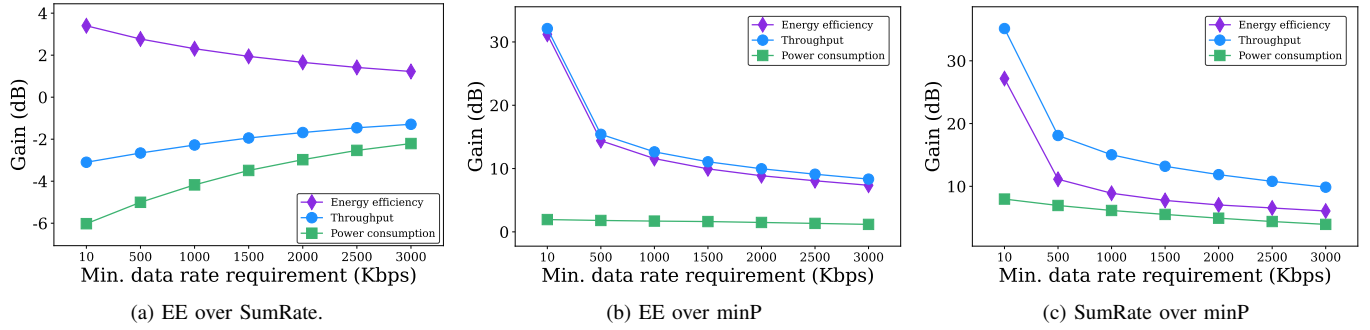


Fig. 4. Gains and losses maintained by EE over SumRate and minP.

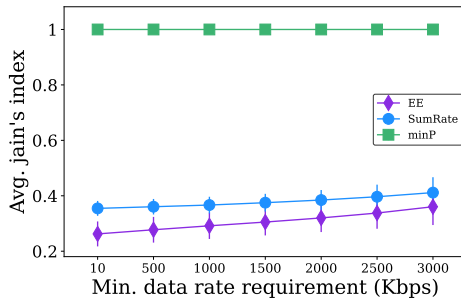


Fig. 5. Throughput fairness of users considering Jain's fairness index.

by EE over SumRate. When comparing EE with minP, Fig. 4b shows orders of magnitude gain in both energy efficiency and throughput. For  $R^{\min} = 0.5$  Mbps, the optimal operation point for EE requires around  $0.5\times$  more power to achieve an order of magnitude higher EE and throughput. Fig. 4c shows similar trends when comparing SumRate with minP, with not as significant gain in energy efficiency as the throughput.

Regarding fairness, Fig. 5 shows that minP is the fairest approach since minP allocates only  $R^{\min}$  for each user, i.e., all users maintain the same data rate. EE and SumRate, on the other hand, allocate additional power to the cluster-head users (best channel quality user of each BS) and only the minimum power necessary for the rest, resulting in rate disparity among the users, thereby lower fairness. Although the rate difference between cluster-head and non-cluster-head users in EE is smaller, the data rate disparity among cluster-head users is higher for EE than for SumRate, which leads to lower fairness. This happens because for EE the power allocation is even more biased towards the best channel quality users since the objective function decreases with increasing allocated power.

## VI. CONCLUSION

This paper investigates the benefits of joint transmission NOMA over conventional NOMA considering three optimization objectives: throughput maximization, energy efficiency maximization, and power minimization. We formulated and presented the solution steps for making these power allocation problems convex. Our numerical investigation shows that, for the studied two-cell scenario, irrespective of the considered objective, joint-transmission NOMA offers benefits over NOMA only in terms of finding a feasible power allocation setting. Our analysis of the trade-offs shows orders of magnitude difference

(increase) in energy efficiency and throughput when optimizing for energy efficiency over power consumption.

## ACKNOWLEDGMENT

This work has been supported by the University of Twente, under EERI: Energy-Efficient and Resilient Internet project.

## REFERENCES

- [1] M. Vaezi and H. Vincent Poor, "NOMA: An information-theoretic perspective," *Multiple access techniques for 5G wireless networks and beyond*, pp. 167–193, 2019.
- [2] X. Chen, D. W. K. Ng, W. Yu, E. G. Larsson, N. Al-Dahir, and R. Schober, "Massive access for 5G and beyond," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 3, pp. 615–637, 2020.
- [3] S. Rezvani, E. A. Jorswieck, R. Joda, and H. Yanikomeroglu, "Optimal Power Allocation in Downlink Multicarrier NOMA Systems: Theory and Fast Algorithms," *IEEE JSAC*, vol. 40, no. 4, pp. 1162–1189, 2022.
- [4] M. S. Ali, E. Hossain, and D. I. Kim, "CoMP Transmission in Downlink Multi-Cell NOMA Systems: Models and Spectral Efficiency Performance," *IEEE Wireless Comms.*, vol. 25, no. 2, pp. 24–31, 2018.
- [5] Q. Cui, H. Song, H. Wang, M. Valkama, and A. A. Dowhuszko, "Capacity analysis of joint transmission CoMP with adaptive modulation," *IEEE Trans. on Vehicular Tech.*, vol. 66, no. 2, pp. 1876–81, 2016.
- [6] S. R. C. Magalhaes, S. Bayhan, and G. Heijnen, "Impact of Power Consumption Models on the Energy Efficiency of Downlink NOMA Systems," <https://arxiv.org/abs/2304.05183>, Tech. Rep., 2023.
- [7] W. Shin, M. Vaezi, B. Lee, D. J. Love, J. Lee, and H. V. Poor, "NOMA in Multi-Cell Networks: Theory, Performance, and Practical Challenges," *IEEE Comms. Mag.*, vol. 55, no. 10, pp. 176–183, 2017.
- [8] M. S. Ali, E. Hossain, A. Al-Dweik, and D. I. Kim, "Downlink power allocation for CoMP-NOMA in multi-cell networks," *IEEE Trans. on Comms.*, vol. 66, no. 9, pp. 3982–3998, 2018.
- [9] A.J. Muhammed et al., "Resource Allocation for EE NOMA System in CoMP Networks," *IEEE TVT*, vol. 70, pp. 1577–91, 2021.
- [10] Y. Fu, Y. Chen, and C. W. Sung, "Distributed power control for the downlink of multi-cell NOMA systems," *IEEE Transactions on Wireless Communications*, vol. 16, no. 9, pp. 6207–6220, 2017.
- [11] Z. Liu, G. Kang, L. Lei, N. Zhang, and S. Zhang, "Power Allocation for Energy Efficiency Maximization in Downlink CoMP Systems with NOMA," in *IEEE Wireless Comms. and Nw. Conference*, 2017.
- [12] A. Zappone and E. Jorswieck, "Energy efficiency in wireless networks via fractional programming theory," *Foundations and Trends in Comms. and Information Theory*, vol. 11, no. 3–4, pp. 185–396, 2015.
- [13] 3GPP, "Technical specification group radio access network; evolved universal terrestrial radio access (e-utra); radio frequency (rf) requirements for lte pico node b (release 13)," Tech. Rep., 2016.
- [14] R. Jain, D. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared systems," Tech. Rep., 1984, digital Equipment Corporation, Technical Report DEC-TR-301.