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Spectral and energy efficiencies maximization in downlink NOMA systems

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ABSTRACT

Due to the huge connectivity and ever-growing demands of diverse services and high data rate applications, more effective radio access techniques are required for the next generation wireless systems. Non-orthogonal multiple access (NOMA) is a promising candidate which has been recognized as an effective multiple access technique that notably improves the spectral efficiency (SE). In addition to SE, energy efficiency (EE) is also attracting too much interest nowadays due to the limited power of end users (EU) and internet of things (IoT) devices, and the strict environmental concerns related to global carbon dioxide (CO_2) emission of communication devices. However, in fact there is a trade-off relationship between SE and EE. In this paper, the SE-EE trade-off relationship in NOMA-based systems is mathematically modeled and analyzed. On the other hand, in order to attain an elastic SE-EE trade-off relationship, the problem is formulated as an optimization problem with an objective of maximizing the EE under the constraint of satisfying a minimum SE demand. Simulation results confirmed the theoretical findings of this study and further asserted the validation of the proposed power allocation scheme which aims to achieve a more flexible trad-off relationship between SE and EE.

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1. INTRODUCTION

Emerging communication networks, such as 5G and beyond, face challenging requirements arising from anticipated use scenarios including IoT, low latency or real time communications, and enhanced mobile broadband [1]. To accommodate such high demands in the future 5G mobile networks, there is a need for new architectures and efficient multiple access (MA) techniques that can support a high data rate, high spectral efficiency, and low latency [2]. Different orthogonal multiple access (OMA) techniques were used in previous generations of communication systems. For 5G and beyond, these OMA techniques cannot achieve the required demands (i.e.: sum rate capacity), because OMA techniques are not adequate to support the emerging wireless applications with enormous connectivity and various quality-of-service (QoS) demands [3].

As a result, non-orthogonal multiple access (NOMA) has been specified as a promising MA technique of the next generation wireless systems, which can support superior SE [4]. There are two main types of NOMA called power domain NOMA (PD-NOMA) and code domain NOMA (CD-NOMA) [5]. PD-NOMA is the more common, famous, and favorable candidate for 5G multiple access; therefore, it's selected in this paper. NOMA exploits multiplexing in the power-domain to handle the information transmission of multiple users, where the main operating principle of NOMA is to allow non-orthogonal spectrum usage by multiple users at the same time, frequency, and code [6]. Figure 1 shows the NOMA power domain multiplexing versus OMA time division multiple access (TDMA) technique.

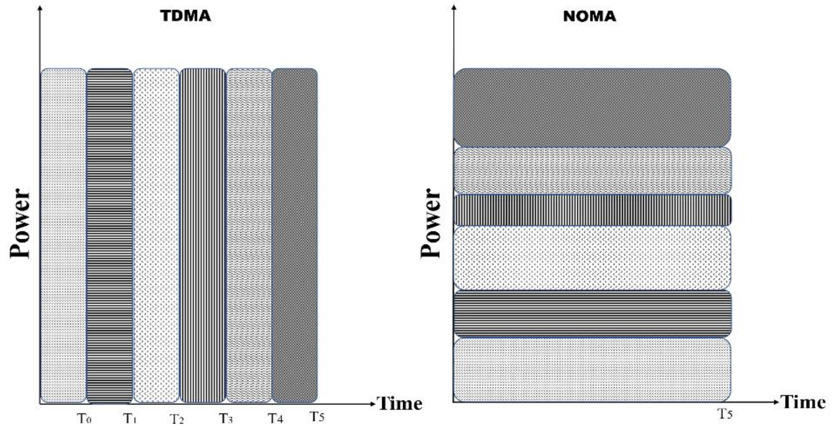

Figure 1. NOMA vs TDMA (OMA) [7]

In NOMA-based systems, the spectral efficiency (SE) (achievable sum-rate) is logarithmically increased with maximum transmit power, while EE is reversely proportional to the total consumed power which is an affine function of the maximum transmit power [8]. As a result, there is a non-negligible trade-off relationship between SE and EE. This trade-off relationship is the key reason behind the need for efficient resource allocation designs. Several studies [9]-[16] have proposed different optimization techniques for the purpose of allocating the system resources effectively. In [9], [10] different strategies were used to allocate the power in downlink NOMA (DL-NOMA) systems for the objective of maximizing the throughput of the system. Furthermore, in [11], [12], the EE optimization problem for the same kind of systems were studied. But, to the best of our knowledge, the trade-off problem between SE and EE has not been covered very well for NOMA-based systems. The study of this problem in NOMA-based systems and especially in DL-NOMA systems is quite important, so the EE in NOMA systems can be improved while keeping high SE. In [13] the trade-off problem was studied but in the downlink of an OFDMA system. The SE-EE trade-off relationship problem in relay based Amplify and Forward networks is studied by the authors of [14]. In [15], [16], the SE and EE trade-off problem was studied in a cognitive satellite-vehicular network and in a single-cell massive MIMO downlink transmission with statistical channel state information at the transmitter (CSIT) respectively.

In this paper, the SE-EE trade-off relationship in NOMA-based systems is mathematically modeled and analyzed. Where SE is defined as the ratio of throughput to bandwidth and it is considered as one of the most important metrics in wireless networks [17]. While the other important metric which has been ignored previously by many of researchers and has become an unavoidable tendency lately is EE. EE is defined as a measure of how many bits can be transmitted utilizing a Joule of energy [18]. Finally, to attain an elastic SE-EE trade-off relationship (make a balance between the two conflicting metrics) in emerging wireless networks, this study focused on SE-EE trade-off problem in DL-NOMA systems. The problem is formulated as an optimization problem with an objective of maximizing the EE under the constraint of satisfying a minimum SE demand. Furthermore, the QoS demands of each user are determined and satisfied by a requirement of minimum data rate. The optimization problem is formulated as a bi-layer problem because the system EE is demonstrated to be an exactly quasi-concave function of transmitted power and then the closed-form solutions to the problem have been obtained.

The remaining of this paper is formulated as follows: section 2 covers the basic concepts of NOMA (especially PD-NOMA) and shows the superposition coding (SC) and successive interference cancelation (SIC) processes performed at the transmitter and receiver respectively. The trade-off between SE and EE is modeled mathematically and analyzed, the problem is formulated as an optimization problem, and the closed-form solutions to the problem have been obtained in section 3. The simulation results and discussions are presented in section 4. While section 5 concludes the paper.

2. BASIC CONCEPTS OF NOMA

As a multiple access (MA) technique for the next generation of wireless communication systems, NOMA (especially PD-NOMA) has been widely recognized as a promising candidate [19]. In NOMA, multiple users can access the same time-frequency resource in power domain via SC at the transmitter side and SIC at the receiver side [20]. In addition to the enhancement of system's SE and EE, NOMA also supports more users when compared with the conventional orthogonal multiple access (OMA). At the same time, the user fairness is also improved by NOMA [21].

The basic idea of SC is to encode various signals prepared for distinct users with different levels of power at the transmitter side. SC assists the receiver to implement multiuser detection successively [22]. In NOMA-based systems, the link from base-station to end-users (EU) is known as downlink NOMA, and uplink NOMA is in opposite direction from EU to BS. In downlink NOMA, weaker users (users with lower channel gain) are allocated with higher levels of power. On the other hand, lower power levels are assigned to stronger users (users with higher channel gain) [23]. At the other end, SIC is applied at the stronger user in receiver side in the case of downlink-NOMA. Stronger user make use of SIC to decode the received signals by sequentially decoding and subtracting the signals intended for the weaker users first. in other words, the signal of weakest user is firstly decoded and subtracted from the received signal. then the execution of SIC process continue until the signals of all weaker users are decoded sequentially and the strongest user own signal is decoded lastly [24].

To further illustrate the concept, a simple 2-user, single input-single output (SISO) NOMA-based system is considered. As shown in Figure 2, for this proposed system model with one base station (BS) and two users, (U_1) is assumed to have a better channel quality (strong user) than (U_2) with worse channel quality (weak user), i.e., $|h_1|2 \geq |h_2|2$, where h_i is the channel coefficient between U_i and the BS and $h_i = g_i \,.\, \rho l^{-1}(d_i)$, where g_i is the coefficient of Rayleigh fading and $\rho l^{-1}(d_i)$ is the path loss function induced by the distance (d) between U_i and the BS. Then, based on SC, different levels of power are used to encode the signals of the users, therefore; the transmitted signal from the BS is written as:

$$x = \sqrt{\alpha_1 p}\, m_1 + \sqrt{\alpha_2 p}\, m_2 \tag{1}$$

where $\sqrt{\alpha_i p}$ represents the transmit power allocated for U_i, and m_i represents the transmitted message (symbol) of U_i. More power is assigned to the weak user (U_2) based on the concepts of SC, i.e., $\alpha_2 \geq \alpha_1$. Then the superimposed signal received by U_i can be written as:

$$y_i = h_i * x + n_i \tag{2}$$

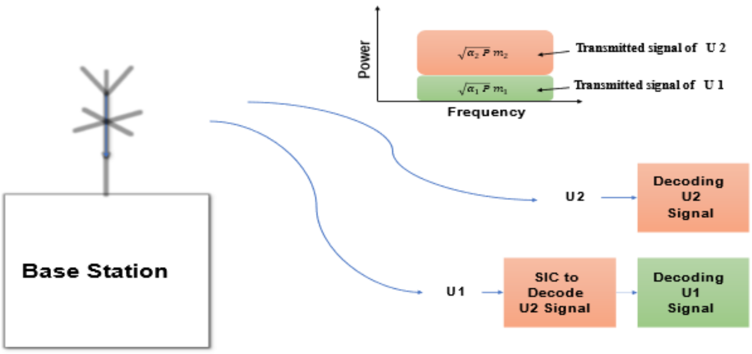

Figure 2. System model of downlink-NOMA [25]

where n_i is additive white Gaussian noise (AWGN) at U_i with zero mean and a noise power (variance) of σ^2. Then, based on the concepts the strong user has to perform SIC, therefore; U_1 will first decode the signal of weak user (U_2) and subtract it from the received signal to eliminate the Inter-user-interference (IUI) of U_2. So, it is not required from U_2 to do any interference cancelation, it just decodes its own message m_2 directly. As this system model implies a degraded broadcast channel [26], the following corresponding achievable rates can be obtained easily [27]:

$$R_1 = W\, log_2\left(1 + \frac{|h_1|^2 \alpha_1\, p}{\sigma^2}\right) \tag{3}$$

$$R_2 = W\ log_2\ \left(1 + \frac{|h_2|^2 \alpha_2\ p}{|h_2|^2 \alpha_1\ p + \sigma^2}\right) \tag{4}$$

where R_1 indicate the achievable rate for U_1 to decode its own message after decoding and subtracting the signal of weak user (U_2), and R_2 indicates the achievable rate for U_2 to decode its own message by treating the signal intended for the strong user (U_1) as interference. For the proposed system model, the system sum-rate of downlink-NOMA can be written as:

$$R_{sum}^{DL} = W\ log_2\ \left(1 + \frac{|h_1|^2 \alpha_1\ p}{\sigma^2}\right) + W\ log_2(1 + \frac{|h_2|^2 \alpha_2\ p}{|h_2|^2 \alpha_1\ p + \sigma^2}) \tag{5}$$

It can be noticed from (5) that the interference caused by U_1 for U_2 cannot be eliminated by SIC.

3. SE-EE TRADE-OFF PROBLEM OPTIMIZATION IN DL-NOMA SYSTEM

In addition to SE, EE has also emerged as a new distinguished and essential target for wireless communication systems due to the major issues related to the energy consumptions and environment problems. EE can be mainly considered as a benefit-to-cost ratio [28], [29]. Based on the achievable sum-rate formula, the EE of DL-NOMA systems can be written as:

$$\eta_{EE}^{DL} = \frac{R_{sum}^{DL}}{W(\mu(\alpha_1\ p + \alpha_2\ p) + p_{st})} = \frac{log_2\left(1 + \frac{|h_1|^2 \alpha_1\ p}{\sigma^2}\right) + log_2\left(1 + \frac{|h_2|^2 \alpha_2\ p}{|h_2|^2 \alpha_1\ p + \sigma^2}\right)}{\mu(\alpha_1\ p + \alpha_2\ p) + p_{st}} \tag{6}$$

where the inefficiency of power amplifier is captured if the constant μ is greater than 1 ($\mu > 1$) and p_{st} is the static hardware power consumption related to both transceiver of NOMA-based system. In this study, power amplifier is assumed to operates in linear region and p_{st} is a constant. To explain the main trade-off relationship between SE and EE, the same power is allocated for both users such that $\alpha_1\ p = \alpha_2\ p = 0.5p^{max}$, where p^{max} is the maximum transmit power at the transmitter, then:

$$\eta_{EE}^{DL} = \frac{log_2\left(1 + \frac{|h_1|^2\ p^{max}}{2\sigma^2}\right) + log_2\left(1 + \frac{|h_2|^2\ p^{max}}{|h_2|^2\ p^{max} + 2\sigma^2}\right)}{\mu p^{max} + p_{st}} \tag{7}$$

From (7), it can be noticed that there is a significant trade-off relationship between the EE and the achieved sum-rate in DL-NOMA systems. This nontrivial trade-off relationship between EE and SE does a substantial role in energy efficient resource allocation designs of wireless communication systems of both OMA and NOMA multiple access techniques.

In this section, the SE-EE trade-off problem in the DL-NOMA system is formulated as an optimization problem with main objective of maximizing EE via an optimal power allocation strategy and constraint of satisfying minimum SE demand (η_{SE}^{min}). The SE and EE in DL-NOMA system are defined as:

$$\eta_{SE}^{DL} = \frac{R_{sum}^{DL}}{W} \tag{8}$$

$$\eta_{EE}^{DL} = \frac{\eta_{SE}^{DL}}{\mu\ p + p_{st}} \tag{9}$$

To simplify the analysis and without the loss of generality, in this section the equivalent channel gain of user U_i is defined as $G_i = \frac{|h_i|^2}{\sigma^2}$, and the power allocation coefficient (α) and ($1 - \alpha$) are used instead of α_1 and α_2 respectively. Then, the sum rate of DL-NOMA system can be formulated as:

$$R_{sum}^{DL} = W[\ log_2(1 + G_2\ p) + log_2\ (\frac{1 + \alpha\ G_1\ p}{1 + \alpha\ G_2\ p})] \tag{10}$$

So, as (η_{SE}^{DL}) $is\ a$ monotone increasing function of transmit power (p), because the ($\frac{d\ \eta_{SE}^{DL}}{d\ p} > 0$), then the constraint of (η_{SE}^{min}) can be replaced by the constraint of minimum transmit power (p^{min}). As a result, it satisfies that $\eta_{SE}^{DL}(p^{min}) = \eta_{SE}^{min}$, and the corresponding minimum sum rate is indicated as $R^{min}= W\ \eta_{SE}^{min}$ according to (8). In addition, the minimum data rate of each user is also considered.

Therefore, the optimization problem is defined as:

$$
\begin{aligned}
& Obj.\, max_{\alpha,p}\ \eta_{EE}^{DL} = \frac{R_{sum}^{DL}}{W(\mu\, p + p_{st})} \\
& S.t.\, C1{:}\ 0 < p \le p^{max}, \\
& C2{:}\ R_{sum}^{DL} \ge R^{min}, \\
& C3{:}\ R_i \ge R_i^{min}, i = 1,2 \\
& C4{:}\ 0 < \alpha \le \gamma < 0.5
\end{aligned} \tag{11}
$$

where R_i^{min} is the minimum data rate requirement of U_i . Constraint C2 guarantees the minimum SE demands of the system and the minimum data rates of users are guaranteed by C3. According to the NOMA principle, C4 ensures that the weak user's transmit power is greater than that of strong user, where γ is a constant less than 0.5. In this section analysis, we always assume that $p^{max} \ge p^{min}$ and $R^{min} \ge R_1^{min} + R_2^{min}$. Therefore, due to the last assumption and the fact that R_{sum}^{DL} is a monotone increasing function of p, p^{min} can always satisfy the data rate demands of both users. The presence of interference term in the objective function makes the problem to act as a non-convex optimization problem [30]. Therefore, to handle the optimization problem suitably, the problem of maximizing the EE of the system is studied first without the consideration of system SE requirement. The problem of EE maximization for a given p can be re-written as:

$$
\begin{aligned}
& \text{Obj.}\, max_{\alpha}\ \eta_{EE}^{DL} = \frac{R_{sum}^{DL}}{W(\mu\, p + p_{st})} \\
& \text{S.t.}\, C1{:}\ R_i \ge R_i^{min}, i = 1,2 \\
& C2{:}\ 0 < \alpha \le \gamma < 0.5
\end{aligned} \tag{12}
$$

Now, we assume that the minimum data rates of both users are the same $R_1^{min} = R_2^{min} = R_u^{min}$. Then, for a given p, maximizing η_{EE}^{DL} is equivalent to maximizing R_{sum}^{DL} as the denominator of objective function is a constant. Furthermore, the maximization of R_{sum}^{DL} is equivalent to the maximization of $\varphi(\alpha)$ for a given power. According to (10), $\varphi(\alpha)$ can be defined as:

$$
\varphi(\alpha) \triangleq\ log_2 \left(\frac{1 + \alpha\, G_1\, p}{1 + \alpha\, G_2\, p}\right) \tag{13}
$$

$\varphi(\alpha)$ is a monotone increasing function of α, because the $(\frac{d\, \varphi(\alpha)}{\mathrm{d}\, \alpha} > 0)$; therefore, under the same constraints, the problem of maximizing $\varphi(\alpha)$ can be transformed to the problem of finding the upper bound of α. As a result, the optimization problem in (12) is formulated as:

$$
\begin{aligned}
& Obj.\, max_{\alpha}\ \alpha \\
& S.t.\, C1{:}\ \alpha \ge \alpha_l \\
& C2{:}\ \alpha \le \alpha_u \\
& C3{:}\ 0 < \alpha \le \gamma < 0.5,
\end{aligned} \tag{14}
$$

where α_l is the lower bound of α and based on (3) and constraint C1 in (12), it is defined as:

$$
\alpha_l \triangleq \frac{V}{G_1\, p} \tag{15}
$$

where $V = 2^{\frac{R_u^{min}}{w}} - 1$. Similarly, α_u is the upper bound of α and based on (4) and constraint C1 in (12), it is defined as:

$$
\alpha_u \triangleq \frac{G_2\, p - V}{(1+V) G_2\, p}\ (16) \tag{16}
$$

The relation between the power (p) and the lower and upper bound of α is shown in Figure 3.

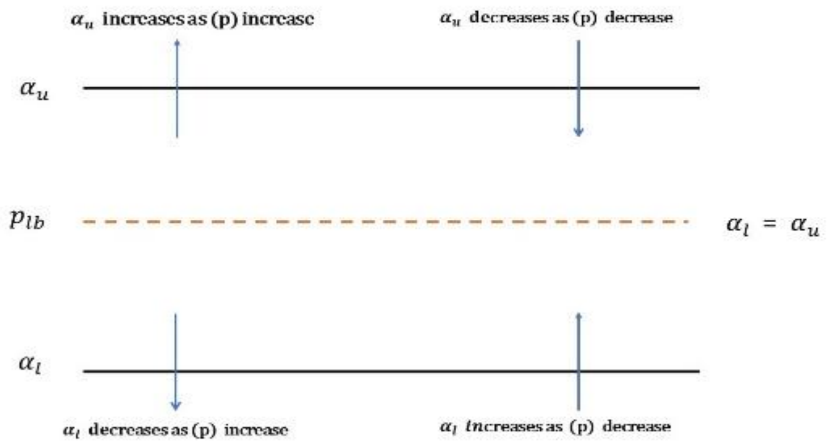

Figure 3. The relationship between the power (p) and the lower and upper bound of (α).

It can be noticed that α_u increases or decreases with the increase and decrease of power respectively. While α_l decreases as power increase and vice versa. The lower bound of power (p_{lb}) is satisfied with the condition ($\alpha_l = \alpha_u$) and can be defined as:

$$p_{lb} = \frac{V\,(1+V)}{G_1} + \frac{V}{G_2} \quad (17)$$

when $p = p_{lb}$, the data rates of both users are equal to R_u^{min}. Therefore, to ensure that the functional domain of (α) has practical importance, p must be large enough, because when $p \geq p_{lb}$, α_l is less than or equal to α_u . Since it's proofed in [31] that η_{EE}^{DL} is a strictly quasi-concave in p, the original optimization problem (11) is divided into two layers and then solved:

a. Layer 1:

Find optimal value of (α) among both users with taking the feature of NOMA and the QoS demands of each user into consideration. The optimal value of (α) can be determined in one of the following cases:

Case1: when $R_u^{min} \geq W \log_2(1 + \frac{(1-\gamma)\, G_2\, p}{1+\gamma\, G_2\, p})$, $0 < \alpha_u \leq \gamma$, the optimal solution to (14) is $\alpha^{opt} = \alpha_u$. Which shows that to maximize the EE of the system, the power allocated to U_2 (weak user) can just satisfy its minimum data rate requirement in the scheme of optimal power allocation.

Case2: when $R_u^{min} < W \log_2(1 + \frac{(1-\gamma)\, G_2\, p}{1+\gamma\, G_2\, p})$, $\alpha_u > \gamma$, the optimal solution to (14) is $\alpha^{opt} = \gamma$. Which shows that the power allocation ratio of U_1 to U_2 can be fixed, if the minimum date rate requirement is relatively low. In addition, the data rates of both users are greater than the minimum data rate requirement R_u^{min}.

b. Layer 2:

Find optimal value of (p) with taking the maximum available power (p^{max}) and the SE requirement of the system into consideration. Since we have assumed that ($p^{max} \geq p^{min}$) is always true, there are only three possible cases for the $\eta_{EE}^{DL} - to - p$ relationship:

Case1: the optimal solution to the optimization problem (11) is obtained at $p^{opt} = p^{min}$, if $\frac{d\,\eta_{EE}^{DL}}{d\,p}\Big|_{p=p^{min}} \leq 0$, which indicates the strict decrease of η_{EE}^{DL} with p for $p \in [p^{min}, p^{max}]$.

Case2: the optimal solution to the optimization problem (11) is obtained at $p^{opt} = p^{max}$, if $\frac{d\,\eta_{EE}^{DL}}{d\,p}\Big|_{p=p^{max}} \geq 0$, which indicates the strict increase of η_{EE}^{DL} with p for $p \in [p^{min}, p^{max}]$.

Case3: the optimal solution to the optimization problem (11) is obtained at $p^{opt} = \mathrm{p_{mp}}$. Where $\mathrm{p_{mp}}$ is the maximum point in the curve of $\eta_{EE}^{DL} - to - p$ relationship and can be found via bisection search method.

The optimal solution at $p^{opt} = \mathrm{p_{mp}}$ is obtained if $\frac{d\,\eta_{EE}^{DL}}{d\,p}\Big|_{p=p^{min}} > 0$ and $\frac{d\,\eta_{EE}^{DL}}{d\,p}\Big|_{p=p^{max}} < 0$, which indicates both the strictly increase and then strictly decrease of η_{EE}^{DL} with p for $p \in [p^{min}, p^{max}]$.

After the two layers decomposition of the original optimization problem (11), now it can be solved by applying the algorithm of optimal power allocation as shown in Algorithm 1.

Algorithm 1. Optimal power allocation algorithm

1: Initialize the transmit power $p^{(1)} = p^{min}$, $p^{(2)} = p^{max}$, the iteration index t = 1, and the tolerance *tol* = 0.0001.
2: For a given $p^{(1)}$, optimize over $\alpha^{(1)}$, and calculate *dvt_1* $= \frac{d\,\eta_{EE}^{DL}}{d\,p}|_{p=p^{(1)}}$.
3: If *dvt_1 ≤ 0*, then
4: Output $\alpha^{opt} = \alpha^{(1)}$ and $p^{opt} = p^{(1)}$;
5: Else
6: For a given $p^{(2)}$, optimize over $\alpha^{(2)}$, and calculate *dvt_2* $= \frac{d\,\eta_{EE}^{DL}}{d\,p}|_{p=p^{(2)}}$.
7: End If
8: If *dvt_2 ≥ 0*, then
9: Output $\alpha^{opt} = \alpha^{(2)}$ and $p^{opt} = p^{(2)}$;
10: Else
11: *x* = $p^{(1)}$, *y* = $p^{(2)}$, *f(x) = dvt_1, and f(y) = dvt_2*
12: *z = (x + y)/2, f(z) =* $\frac{d\,\eta_{EE}^{DL}}{d\,p}|_{p=z}$.
13: While *|f(z)| ≥ tol* do
14: If *f(x) f(z) > 0* then
15: *x = z, f(x) = f(z);*
16: Else
17: *y = z, f(y) = f(z);*
18: End If
19: *t = t+1;*
20: *z = (x + y)/2, f(z) =* $\frac{d\,\eta_{EE}^{DL}}{d\,p}|_{p=z}$.
21: End While
22: End If
23: Output $\alpha^{opt} = \alpha^{(t)}$ and $p^{opt} = p^{(t)}$;

4. SIMULATION AND RESULTS

Anaconda [32] is an open-source and free distribution of Python programming language, where Python [33] is an interpreted and high-level programming language. Anaconda navigator is a graphical user interface (GUI) tool included in the Anaconda distribution and makes it easy to configure, install, and launch tools such as Jupyter notebook, which is a shareable notebook that combines live code, visualizations and text. For the evaluation purposes of this paper, the simulation results are obtained by using Anaconda Navigator, Jupyter notebook, and Python programming language. The simulation results are obtained by performing two different scenarios with general focus on the second scenario.

At the beginning, the trade-off relationship between SE and EE is illustrated. In this scenario it's assumed that both users are assigned with the same amount of power ($\alpha_1 p = \alpha_2 p = 0.5p^{max}$). Figure 4 and Figure 5 explain the SE and EE trade-off relationship with respect to p^{max} for both NOMA-based and OMA-based systems.

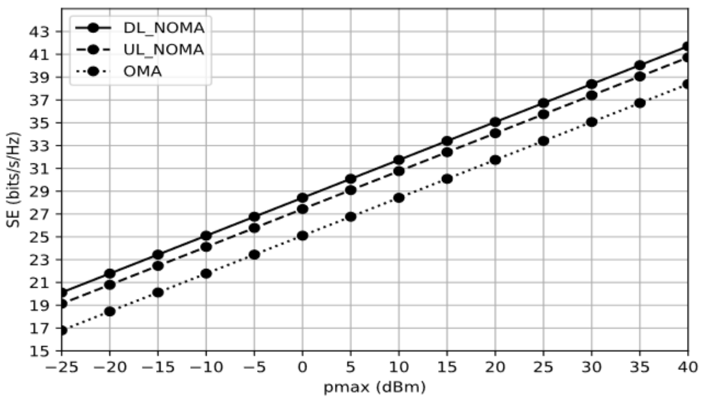

Figure 4. Spectral Efficiency of NOMA (downlink and uplink) and OMA systems versus the transmit power

From Figure 4, it can be noticed that the spectral efficiency of both NOMA-based (DL and UL) and OMA-based systems is effectively increased with respect to p^{max}. While for Figure 5, the curves of the three schemes [p_{st}=1 W, p_{st}=2 W, and p_{st}=3 W] have the same tendency. In more details, all the three schemes have similar performance in SNR domains (in both low and high SNR regions). As shown in Figure 5, it can be noticed that for the three different schemes the EE of the system increases with (p^{max}) at the beginning and then decreases with (p^{max}). In more details, the EE of the system is mostly restricted by the static hardware (circuit) power consumption (p_{st}) when (p^{max}) is small. Furthermore, when the transmit power (p^{max}) is increased, both the achievable sum-rate and EE of the system are effectively increased, because in the low SNR domain, the achievable sum-rate of the system tabulates nearly linearly with respect to (p_{max}).

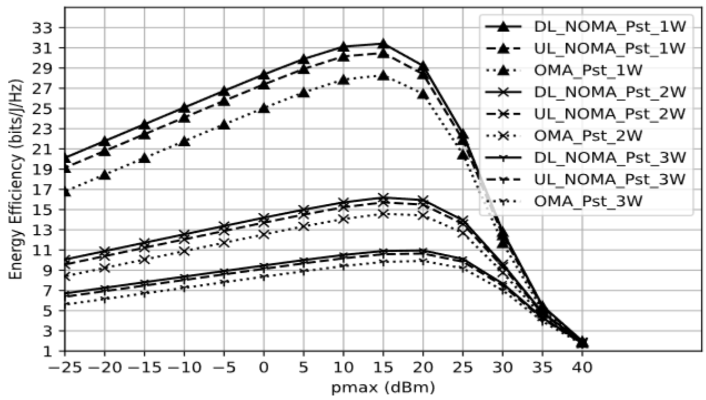

Figure 5. Trade-off between EE (bits/J/Hz) and transmit power ($\boldsymbol{p^{max}}$ (dBm))

On the other hand, the transmit power (p^{max}) is controlling the total power consumption in the domain of high SNR. Therefore, further increase in (p^{max}) would decrease the EE of the system rapidly after reaching the maximum system energy efficiency, as shown in Figure 5. Additionally, the movement of the optimal operation point (maximum system energy efficiency) toward the high SNR domain can be observed very clearly with increasing (p_{st}). because as (p_{st}) is larger, that means that higher (p^{max}) is needed to outweigh the effect of (p_{st}) on the EE of the system. As a result, to obtain a maximum energy efficiency for practical systems (p_{st}>0), there is a need for effective resource allocation designs in order to find the optimal operation point.

Therefore; in the second scenario, numerical results are presented to confirm our theoretical findings and to evaluate the performance of our proposed resource allocation strategy for DL-NOMA systems. For the system model of Figure 2, A single cell with 2 uniformly distributed users, 500m cell radius, and minimum distance of 50m between users and BS is considered. The total bandwidth of the system is 1MHz. The power spectral density of the AWGN is -174 dBm/Hz and the exponent of path loss is set to be 3. The static hardware (circuit) power consumption (p_{st}) is set to have three different values (p_{st}=1 W, 2W, and 3W). We assumed that the minimum data rates of both users are the same $R_1^{min} = R_2^{min} = R_u^{min}$. To ensure the QoS of each user, the minimum data rate requirements are introduced as R_u^{min}=1Mbps. Figure 6 shows the optimal EE of the system versus the maximum available transmit power at the transmitter (p^{max}) for the proposed algorithm of this study, the algorithm proposed in [34] for DL-NOMA system (we referred to as NAZ based on the abbreviation of the first author's name of the study), and the algorithm proposed for OFDM system in [35].

From Figure 6, it can be noticed that the optimal EE of the system is first increased with p^{max}. But, once p^{max} has reached a certain threshold, the optimal EE of the system remains unchanged for our proposed scheme. This is due to the fact that when p^{max} is relatively low, all the available power at the base station is being used according to the optimal transmit power selection strategy. However, when p^{max} is large enough, the optimal transmit power is set by the optimal transmit power selection strategy to be equal to the power of the maximum point in the curve of $\eta_{EE}^{DL} - to - p$ relationship ($p^{opt} = \mathrm{p_{mp}}$) regardless of how much p^{max} is available.

On the other hand, it can be noticed very clearly that the optimal EE of the system obtained via the proposed algorithm of this study outperforms that of [34] for DL-NOMA and [35] for OFDMA with the same system model been proposed by them too. Furthermore, it can also be seen that the optimal EE of the system strictly decreases with the static hardware (circuit) power (p_{st}). Figure 7 shows the effect of (p_{st}) on the optimal EE of the system. But as can be noticed from this Figure, the proposed algorithm in this study is outperforming the proposed algorithm by [34] for DL-NOMA system regardless of the value of (p_{st}).

The optimal transmit power versus maximum transmit power (p^{max}) is shown in Figure 8. It can be seen, that the optimal transmit power first increases with p^{max}, but once p^{max} reaches a certain threshold, The optimal transmit power remains unchanged. Simply, this is due to the fact that when p^{max} is small, all the available power at the base station is being used by the optimal transmission strategy. Therefore, the optimal transmit power increases linearly with p^{max} at the beginning. Because three different (p_{st}) have been used, then the unchanged (fixed) optimal transmit power is referred to as p^{opt} (p_{st}) for any given (p_{st}). Then, when p^{max} reaches a certain threshold, the optimal transmit power is set by the optimal transmission strategy as $p^{opt}= p^{opt}$ (p_{st}), regardless of the value of the available p^{max}. When p^{max} is large enough, it can also be noticed that the optimal transmit power strictly increases with p_{st}. This is due to the fact that as Pst increases, the maximum point of the $\eta_{EE}^{DL} - to - p$ curve is also strictly increases.

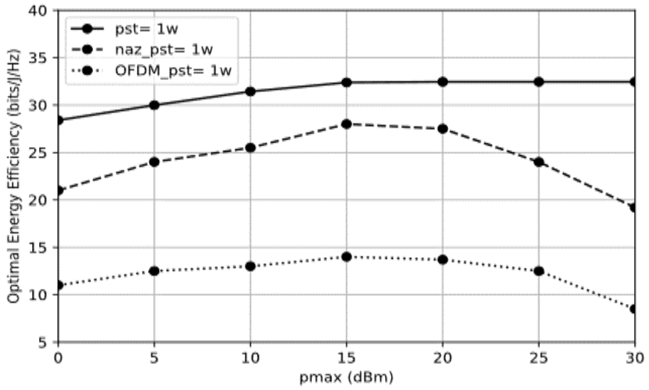

Figure 6. The optimal EE of the system versus the maximum available transmit power at the transmitter (p^{max})

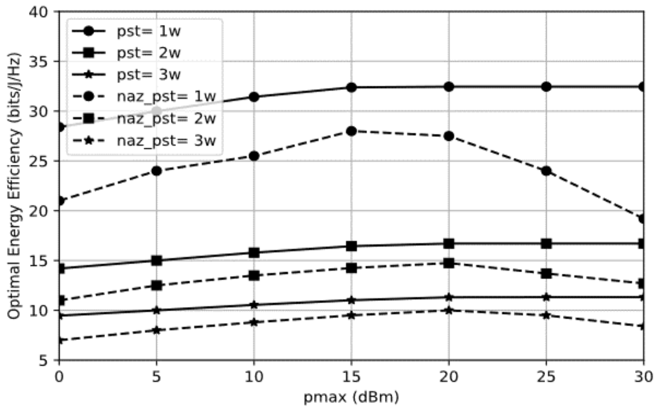

Figure 7. The effect of (p_{st}) on the optimal EE of the system

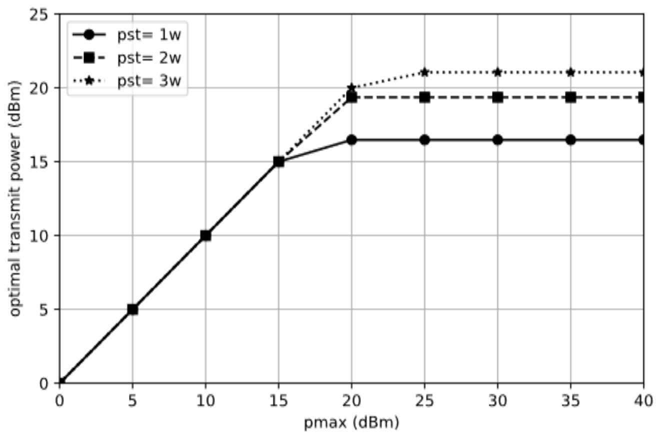

Figure 8. The optimal transmit power versus maximum transmit power (p^{max})

5. CONCLUSION

In this work, an evaluation for the performance of NOMA-based systems is conducted. The trade-off relationship between the system spectral efficiency and energy efficiency is mathematically modeled and analyzed. Mathematical analysis and simulation results show that there is a nontrivial trade-off between SE and EE that should be taken into account when considering resource allocation designs for NOMA-based systems. Therefore; the SE-EE trade-off problem in downlink NOMA systems is considered and formulated as an optimization problem. The basic objective from this optimization problem is to maximize the EE within the framework of satisfying minimum SE with respect of a guaranteed QoS. The decomposition of the problem with the maximization objective into a bilayer optimization problem provided the closed-form solution to the maximization problem. Optimal power allocation coefficients and optimal value of transmit power were both obtained. The results of simulation showed the effectiveness of our proposed algorithm which has better performance than the NAZ and OFDM algorithms with similar if not lower complexity.

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