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Optimal Resource Allocation for NOMA Wireless Networks

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Abstract: The non-orthogonal multiple access (NOMA) method is a novel multiple access technique that aims to increase spectral efficiency (SE) and accommodate enormous user accesses. Multi-user signals are superimposed and transmitted in the power domain at the transmitting end by actively implementing controllable interference information, and multi-user detection algorithms, such as successive interference cancellation (SIC), are performed at the receiving end to demodulate the necessary user signals. Although its basic signal waveform, like LTE baseline, could be based on orthogonal frequency division multiple access (OFDMA) or discrete Fourier transform (DFT)-spread OFDM, NOMA superimposes numerous users in the power domain. In contrast to the orthogonal transmission method, the non-orthogonal method can achieve higher spectrum utilization. However, it will increase the complexity of its receiver. Different power allocation techniques will have a direct impact on the system's throughput. As a result, in order to boost the system capacity, an efficient power allocation mechanism must be investigated. This research developed an efficient technique based on conjugate gradient to solve the problem of downlink power distribution. The major goal is to maximize the users' maximum weighted sum rate. The suggested algorithm's most notable feature is that it converges to the global optimal solution. When compared to existing methods, simulation results reveal that the suggested technique has a better power allocation capability.

Keywords: Non-orthogonal multiple access; wireless networks; power domain; 5G networks

1 Introduction

The rapid development of the mobile Internet and the Internet of Things will place more stringent requirements on future wireless communication systems [1]. Therefore, a Non-Orthogonal Multiple Access (NOMA) technique, also known as Layer Division Multiplexing (LDM), has recently been

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proposed as a promising technology for the next generation of digital terrestrial television (DTT), which provides a simultaneous transmission of fixed and mobile services on the same radio frequency (RF) channel. Non-orthogonal multiple access (NOMA) [2] has the advantages of low latency, high transmission rate, high connection density, etc. [3], and is considered to be one of the technologies to solve the massive user access in future communications. NOMA overcomes the shortcomings of low spectrum utilization in traditional orthogonal multiple access, and it will be more widely used in mobile communications.

The concept of the Internet of Everything has gained traction in the industry as a result of the advancement of Internet of Things technology. On the one hand, realizing vast connections with limited communication resources is a big issue in the Internet of Things' information transmission; on the other hand, low-cost communication nodes account for a significant percentage. These communication nodes are difficult to execute sophisticated tasks due to equipment expense limitations. As a result, achieving dependable communication while keeping equipment costs low is a major difficulty. The core premise of NOMA technology is that the transmitter assigns different strengths to different users' signals, while the receiver utilizes successive interference cancellation first when demodulating lower-power signals.

With the rapid growth of mobile communications, there is a growing demand for spectrum efficiency and system capacity [4]. Because the existing multiple access method can no longer meet development objectives, the industry has introduced NOMA, a new multiple access method. NOMA, as one of the fundamental technologies for 5G, enables multi-user power sharing by providing various powers to users on the same frequency at the same time, resulting in a 50 percent increase in overall wireless access [5–7]. Existing research shows that NOMA can obtain higher system capacity and higher spectrum efficiency than Orthogonal Multiple Access (OMA), so the power allocation problem in NOMA system has attracted widespread attention in the academic community in recent years. Strong signal interference is eliminated by the technology, and when demodulating a signal with a higher power, the signal with a lower power is directly recognized as interference. NOMA is recognized as one of the future network's potential multiple access technologies, and it has gotten a lot of attention [8].

The conjugate gradient approach is used in this research to provide a rapid power distribution strategy that is less difficult than FSPA. The performance is superior to FPA and FTPA, and it achieves a balance between system complexity and performance.

2 Literature Review

The evolutionary process of mobile networks has allowed the strong demands of users to use more efficient services with high data transmission speeds. However, the number of users and the required services are constantly increasing, which has led to a greater development of previous technologies that meet these requirements, being so, after the launch of the known generations, the deployment of the mobile network of fifth generation (5G).

For the research on the power allocation algorithm in the NOMA system, the objective function is mainly focused on minimizing the total transmit power [9–13], minimizing the probability of outage [14–17], and maximizing system throughput [18–20], etc. The main existing algorithms full search power allocation (FSPA) [21], fixed power allocation (FPA) [22], iterative water-filling power allocation (IWPA) [23], and fractional transmit power allocation (FTPA) [24]. Reference [21] pointed out in the study of power allocation and interference cancellation algorithms for non-orthogonal multiple access systems that FSPA can achieve the best performance of non-orthogonal multiple access systems

by searching for all user-pair power allocation combinations, but FSPA has high complexity. The problem is that the system cost is relatively large, so it is generally not used in the actual system. Although FPA is relatively low in complexity, the system performance is greatly affected by the power allocation factor, and usually cannot achieve the best performance of the system. Reference [23] pointed out in the study of non-orthogonal multiple access systems that IWPA can achieve better power distribution performance, but it has problems with local optimization and high complexity. Reference [24] and others proposed the FTPA algorithm. FTPA balances the fairness of users with low signal-to-noise ratio and reduces the complexity of decoding at the receiving end. However, FTPA is a local optimization scheme, and system performance is also affected by the selected power allocation. The impact of factors, therefore, the FTPA program needs to be further improved.

Since the computational complexity of the conjugate gradient method is equivalent to that of the steepest descent method, but the convergence speed is better than that of the steepest descent method [25], this paper proposes a fast power distribution scheme based on the conjugate gradient method, which has a lower complexity than FSPA. The performance is better than FPA and FTPA, and it achieves a compromise between complexity and system performance.

3 System Model and Optimization Analysis

3.1 System Model

Assuming that the transmitting end of the system adopts the single-antenna transmission mode, and at the same time, on the same frequency resource block, the system schedules N users. After the base station allocates the power of the signals sent to the N users, the signals are linearly superimposed in the power domain, and the transmitted equivalent is complex. The baseband signal [26] can be expressed as:

$$x = \sqrt{\beta_1}s_1 + \sqrt{\beta_2}s_2 + \cdots + \sqrt{\beta_N}s_N \tag{1}$$

Among them, $s_1, s_2, \ldots$, and s_N are the energy normalized signals sent to user 1, user 2, ..., user N $(Es_1 = 1, Es_2 = 1, \ldots, Es_N = 1)$; $\beta_1, \beta_2, \ldots$, and β_N are power distribution factors, satisfying $\sum_{n=1}^{N}\beta_n = 1$. Generally, users farther from the base station will be allocated more power.

After the wireless channel, the received signal [27] of user n $(1 \le n \le N)$ is:

$$y_n = h_n x + w_n \tag{2}$$

Among them, h_n is the channel coefficient, and w_n is the Gaussian white noise including cell interference, which obeys the complex Gaussian distribution with a mean value of 0 and a variance of σ_w^2.

At the receiving end of the NOMA downlink, users use interference cancellation receivers for detection. After other users decode, the interference of this user can be eliminated, so as to achieve correct decoding. Take two users as an example. Assuming that user 1 is far away from the base station, more power will be allocated to user 1. At the receiving end, user 1 can directly decode the desired signal x_1. For user 2, the signal x_1 of user 1 needs to be decoded first, and then the relevant component of x_1 is subtracted from the received signal y_2. Therefore, when user 2 decodes the signal x_2, the interference of x_1 has been removed, so that the signal can be decoded correctly.

Based on the above analysis, for the NOMA system based on the SIC receiver, it is assumed that there are N users. From user 1 to user N, the distance between the user and the base station gradually decreases.

Using Shannon's formula, the reachable capacity of each user can be obtained separately. Assuming that the power allocation factor assigned to user n is β_n, then the reachable capacity of user n is:

$$R_n\left(\beta_n\right) = \log_2\left(1 + \frac{\beta_n\left|\boldsymbol{h}_n\right|^2}{\sum_{j>n}^{N}\beta_j\left|\boldsymbol{h}_n\right|^2 + 1}\right) \tag{3}$$

In order to ensure the fairness of user scheduling, the weighted sum rate R_{sum} is used to maximize user power allocation criteria [26]:

$$R_{\text{sum}} = \sum_{n=1}^{N}\frac{1}{\log_2\left(1 + \left|\boldsymbol{h}_n\right|^2\right)}R_n \tag{4}$$

The above problems can be summarized as the following optimization function:

$$\max R_{\text{sum}} = \sum_{n=1}^{N}\frac{1}{\log_2\left(1 + \left|\boldsymbol{h}_n\right|^2\right)}R_n$$
$$\text{s.t.}\, 0 \leq \beta_N \leq \beta_{N-1} \leq \cdots \leq \beta_1 \leq 1 \tag{5}$$

The optimal power allocation factor can be obtained by seeking the extreme value of the above formula. In order to solve this constrained optimization problem, this paper first uses the interior point penalty function method [27] to transform it into an unconstrained optimization problem, and then uses the conjugate gradient descent method to find the optimal solution. Let $\beta = [\beta_1\,\beta_2\ldots\,\beta_N]^{\text{T}}$.

3.2 Objective Function for Unconstrained Optimization

The interior point penalty function method in the penalty function method is to define the new objective function in the feasible region, so that its initial point and the subsequent iteration point sequence must also be in the feasible region, and penalize points that may deviate from the feasible region, which is equivalent to an obstacle is set on the boundary of the feasible region to prevent the iteration point from crossing beyond the feasible region. Therefore, the interior point penalty function method is also called the obstacle function method. Rewrite Eq. (5) into the following form:

$$\min - \sum_{n=1}^{N}\frac{1}{\log_2\left(1 + \left|\boldsymbol{h}_n\right|^2\right)}R_n$$
$$\text{s.t.}\, \beta_n - 1 \leq 0,\, n = 1,\ldots,\, N$$

$$\beta_{n+1} - \beta_n \leq 0,\, n = 1,\ldots,\, N-1$$

$$-\beta_n \leq 0, n = 1,\ldots,\, N \tag{6}$$

Then the following objective function can be constructed:

$$f = -\sum_{n=1}^{N}\frac{1}{\log_2\left(1 + \left|\boldsymbol{h}_n\right|^2\right)}R_n - u_m\left\{\sum_{n=1}^{N}\left(\frac{1}{\beta_n - 1} - \frac{1}{\beta_n}\right) + \sum_{n=1}^{N-1}\frac{1}{\beta_{n+1} - \beta_n}\right\} \tag{7}$$

Among them, u_m is the penalty factor, which is a descending sequence of positive numbers, namely:

$$u_0 > u_1 > \cdots u_m > u_{m+1} > \cdots > 0, \ \lim_{m \to \infty} u_m = 0 \tag{8}$$

Usually $u_m = 1.0, 0.1, 0.01$ and so on. The termination criterion for the convergence of the interior point penalty function method is as follows:

$$\left\| \boldsymbol{\beta}_m^* (u_m) - \boldsymbol{\beta}_{m+1}^* (u_{m+!}) \right\| \leq \varepsilon_1 \tag{9}$$

$$\left| \frac{f \left(\boldsymbol{\beta}_m^* (u_m) \right) - f \left(\boldsymbol{\beta}_{m+1}^* (u_{m+!}) \right)}{f \left(\boldsymbol{\beta}_m^* (u_m) \right)} \right| \leq \varepsilon_2 \tag{10}$$

Among them, $\boldsymbol{\beta}_m^* (u_m)$ is the best advantage of unconstrained optimization when the penalty factor is u_m.

4 Conjugate Gradient Descent

The conjugate gradient method is an effective algorithm for solving optimization problems. Its iterative formula can be written as:

$$\boldsymbol{\beta}_{k+1} = \boldsymbol{\beta}_k + \alpha_k \boldsymbol{d}_k \tag{11}$$

Among them, α_k is determined by a certain linear search. Existing search algorithms include exact linear search and approximate linear search methods such as: Wolfe linear search, Armijo linear search and Goldstein linear search and so on [28]. The authors in [29] proved the global convergence of the (Polak–Ribière–Polyak) PRP algorithm [30] in the conjugate gradient method when Armijo linear search is used [31,32]. Therefore, this article uses the Armijo linear search algorithm to find the smallest non-negative integer h, so that the step factor $\alpha_k = \rho^h$ satisfies the following conditions:

$$f \left(\boldsymbol{\beta}_k + \alpha_k \boldsymbol{d}_k \right) - f \left(\boldsymbol{\beta}_k \right) \leq -\delta \alpha_k^2 \left\| d_k \right\|^2 \tag{12}$$

where $\rho \in (0, 1)$, $\delta > 0$. $\boldsymbol{d}_k$ is the k-th search direction, which is obtained by the following calculation formula:

$$\boldsymbol{d}_k = \begin{cases} -\mathbf{g}_k, & k = 0 \\ -\mathbf{g}_k + -\gamma_k \boldsymbol{d}_{k-1}, & k > 0 \end{cases} \tag{13}$$

where $\mathbf{g}_k = \nabla f \left(\boldsymbol{\beta}_k \right)$ is the gradient of the function f at the point $\boldsymbol{\beta}_k$. The selection of the parameter γ_k satisfies the conjugacy, and the existing conjugate gradient methods include: Face recognition (FR) algorithm, PRP algorithm, Harmony search (HS) algorithm, collision detection (CD) and diffuse yield (DY) algorithms [33–41]. In this paper, the PRP algorithm is selected to calculate the value of γ_k, and its definition is as follows:

$$\gamma_k^{\text{PRP}} = \frac{\mathbf{g}_k^{\text{T}} \boldsymbol{z}_{k-1}}{\left\| \mathbf{g}_{k-1} \right\|^2} \tag{14}$$

where $\boldsymbol{z}_{k-1} = \mathbf{g}_k - \mathbf{g}_{k-1}$, and $\|\cdot\|$ is the Euclidean norm.

In summary, the steps of the proposed unconstrained power allocation scheme are as follows in Algorithm 1.

Algorithm 1: Conjugate gradient method

1:    Given the initial point $\boldsymbol{\beta}_0$ in the feasible region, $\varepsilon > 0$; Calculate $\mathbf{g}_0 = \nabla f(\boldsymbol{\beta}_0)$ and set $k = 0$.

2:    If $||\mathbf{g}_0|| \leq \varepsilon$, stop the iteration; otherwise, let $\boldsymbol{d}_0 = -\mathbf{g}_0$.

3:    Find the step factor α_k according to the exact linear search and update $\boldsymbol{\beta}_{k+1} = \boldsymbol{\beta}_k + \alpha_k \boldsymbol{d}_k$, $k = k + 1$.

4:    Calculate $\mathbf{g}_k = \nabla f(\boldsymbol{\beta}_k)$, if $||\mathbf{g}_k|| \leq \varepsilon$, stop the iteration; otherwise, go to step (5).

5:    Calculate γ_k using Eq. (9), $\boldsymbol{d}_k = -\mathbf{g}_k + \gamma_k \boldsymbol{d}_{k-1}$.

6:    If $\boldsymbol{d}_k^{\mathrm{T}} \mathbf{g}_k > 0$, set $\boldsymbol{\beta}_0 = \boldsymbol{\beta}_k$, and go to step (1); Otherwise, go to step (3).

After adding constraint conditions, the constraint function based on the conjugate gradient method.

The steps of the rate allocation plan are as follows:

(1) Given the initial point $\boldsymbol{\beta}_0$ in the feasible region, as well as u_0, c, and calculation accuracy ε_1, ε_2, set $m = 0$.

(2) Call the above unconstrained optimization method to find the optimal solution $\boldsymbol{\beta}_m^*$ and $f(\boldsymbol{\beta}_m^*, u_m)$ of f.

(3) Use the termination criterion to judge whether it has converged. If it converges, stop the iteration. The best advantage of the constrained power allocation scheme is $\boldsymbol{\beta}^* = \boldsymbol{\beta}_m^*$. If it does not converge, set $\boldsymbol{\beta}_0 = \boldsymbol{\beta}_m^*(u_m)$, $u_{m+1} = c \cdot u_m$, $m = m + 1$ and transfer to step (2) to continue the calculation.

5 Simulation Results

Assuming that the channel obeys Rayleigh fading, the system performance of the two-user model is simulated. When the transmit power SNR1 of user $1 = 10\,\text{dB}$, and the signal-to-noise ratio difference SNR2-SNR1 of user 1 and 2 are 10, 20, 30 and 40 dB, respectively. The simulation parameters are shown in Tab. 1.

Table 1: Simulation parameters

Parameter	Value
System bandwidth	1 MHz
Base station transmit power	40 dBm
Delay spread	1 µs
Noise power spectral density	$-174\,\text{dBm/Hz}$
Number of cellular users	16~96
Maximum number of superimposed users of subband	2
Time window length	100 ms

The change of the weight and rate R_{sum} of the proposed algorithm with the power allocation factor is shown in Fig. 1. It can be seen from Fig. 1 that:

(1) The choice of power allocation factor directly affects the weighted sum rate;

(2) When the signal-to-noise ratio of user 1 is fixed, as the difference between the two users' signal-to-noise ratio increases, the optimal power allocation factor gradually decreases, which also indicates that the remote user will be allocated more power. It is because the criterion adopted in this article is the principle of fairness of user scheduling;

(3) The greater the difference in signal-to-noise ratio between users, the greater the weighted sum rate of the system.
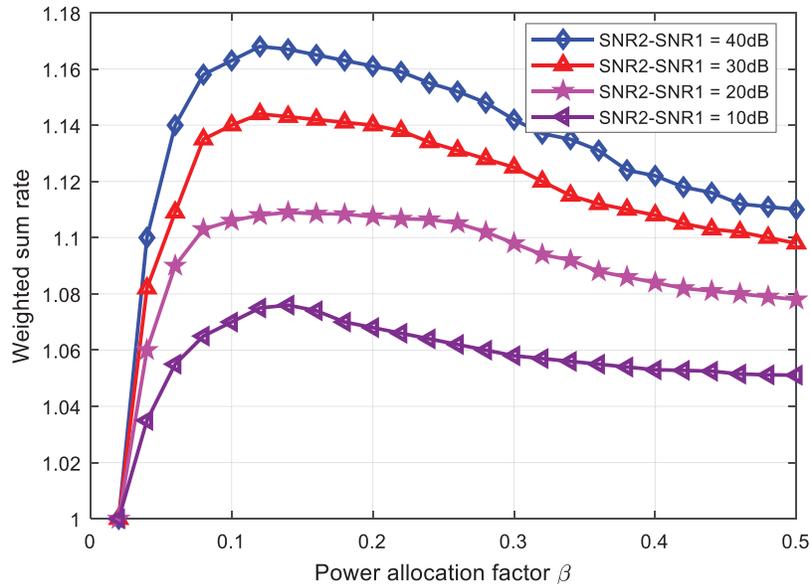
Figure 1: Comparison of the sum rate and power allocation factor of the proposed algorithm

When the difference in signal-to-noise ratio between users is fixed (SNR2-SNR1 = 20 dB) and the signal-to-noise ratio of user 1 is changed, when SNR1 is 2, 4, 6, 8 and 10 dB, the weight and rate of the algorithm in this paper vary with the power allocation factor. The curve is shown in Fig. 2. It can be seen from Fig. 2 that when the SNR difference between users is fixed, the weighted sum rate increases with the increase of user 1 SNR. This is because the difference in the signal-to-noise ratio between users is fixed. When the signal-to-noise ratio of user 1 increases, the corresponding signal-to-noise ratio of user 2 also increases, so the equivalent channel conditions of both users become better, so the weighted sum rate increases.

When the number of users is 2 and SNR1 = 5 dB, the change curve of the weighted sum rate of the NOMA system with SNR2 using the proposed algorithm, FPA algorithm and FTPA algorithm is shown in Fig. 3. The weighted and rate of the NOMA system utilizing the proposed algorithm, the FPA algorithm, and the FTPA method vary with the number of users when the number of users is 3, 4, 5, 6, and 7, as shown in Fig. 4. The system weights and rates of the three algorithms will increase if the signal-to-noise ratio of user 2 improves and the corresponding channel conditions improve, as shown in Figs. 3 and 4. Due to the stronger optimizing ability of the proposed algorithm, it shows significantly better performance than the FPA and FTPA algorithms, and with the increase of the number of users, the performance of the algorithm in this paper is slightly improved. The system weighting and rate will gradually decrease, so the advantages of the proposed algorithm will be more obvious.
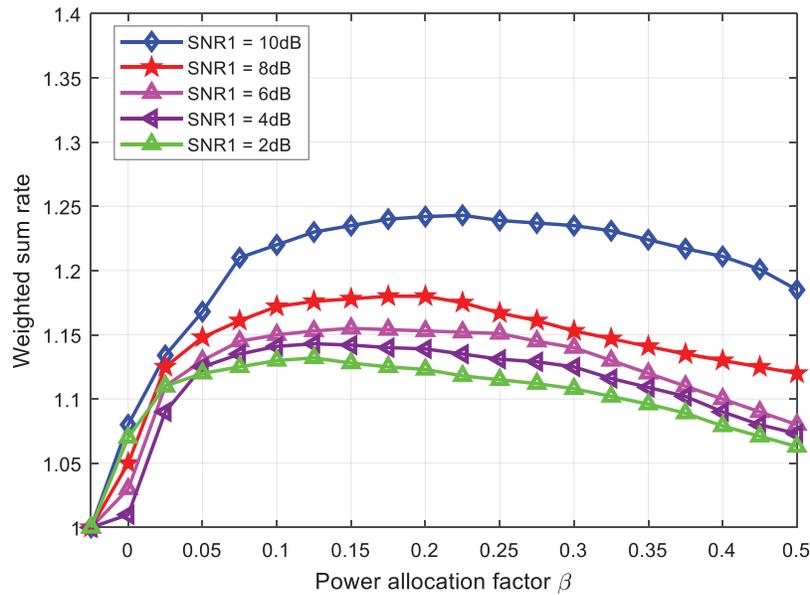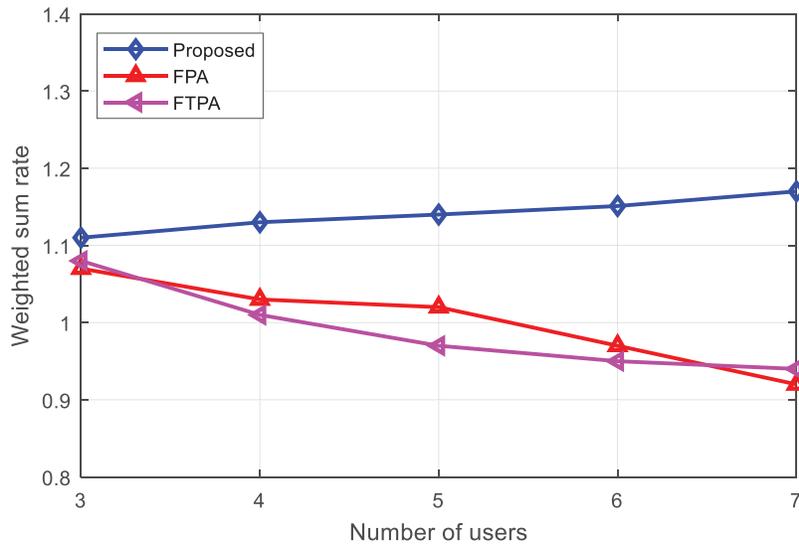
Figure 2: Comparison of the sum rate and power allocation factor of the proposed algorithm with 20 dB SNR difference
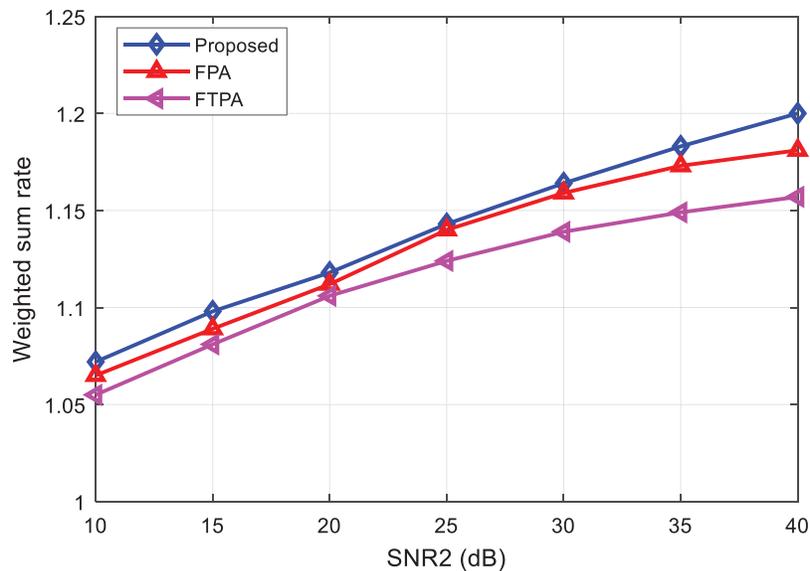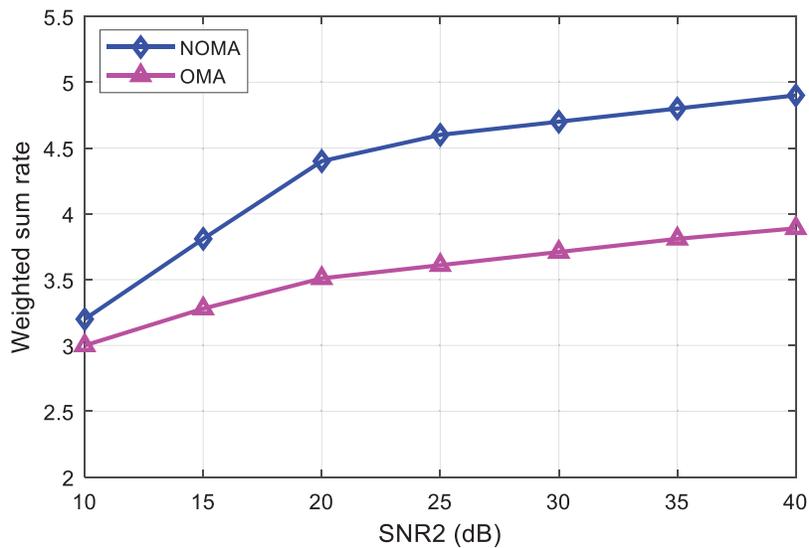

Figure 3: Comparison of the sum rate of the proposed and existing algorithms *vs.* SNR of user two

When the number of users is 2 and SNR1 = 5 dB, the sum rate of the NOMA system and the OMA system using the proposed algorithm varies with SNR2 as shown in Fig. 5. When the number of users is 3, 4, 5, 6, 7, and the sum rate of the NOMA system and the OMA system applying the proposed algorithm is shown in Fig. 6. From Figs. 5 and 6, it can be seen that the performance of the non-orthogonal multiple access system has been significantly improved compared to the orthogonal multiple access system.
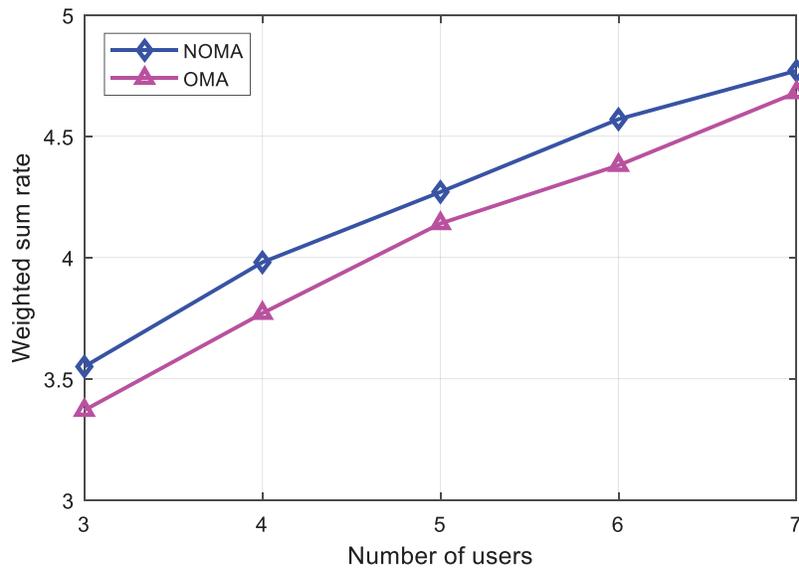
Figure 4: Comparison of the sum rate of the proposed and existing algorithms *vs.* the number of users
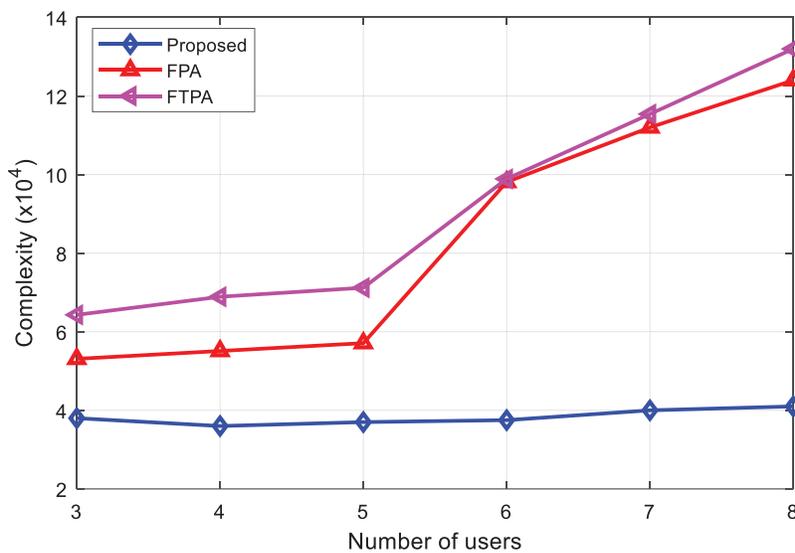

Figure 5: Comparison of the sum rate of the proposed algorithm under NOMA and OMA deployment under SNR variation

Fig. 7 compared the complexities of the proposed and existing algorithms with increasing number of users. It can be seen from Fig. 7 that as the number of users increases, the computational complexities of all the algorithms increases. However, the complexity of the proposed algorithm is much lower and stable than existing algorithms which makes it suitable candidate in terms of hardware implementation with improved energy efficiency.

Figure 6: Comparison of the sum rate of the proposed algorithm under NOMA and OMA deployment under increasing number of users

Figure 7: Complexity comparison of the proposed and existing algorithms

Fig. 8 compared the energy efficiency of the proposed algorithm and existing algorithms under increasing number of users per base station. As can be seen that the energy efficiency of all algorithms increases with increasing the number of users per base station. However, the proposed algorithm provides better energy efficiency than FTPA and FPA algorithms which makes it energy-efficient and computationally efficient.
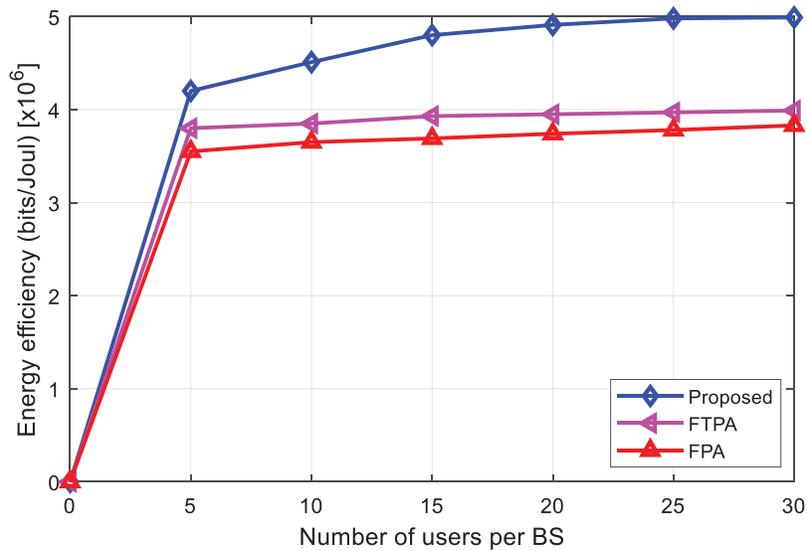
Figure 8: Energy efficiency analysis

6 Conclusion

In contrast to the prior OMA methods that characterized previous generation networks, NOMA is unique in its key design. It uses superposition coding (SC) to allow a transmitter to serve numerous customers at the same time while sharing the same resource blocks (RBs). It distinguishes them in the power domain by allocating various power levels to them, and it performs successive interference cancellation (SIC) at the receiver while allowing restricted multiple access interference (MAI). Aiming at the power allocation problem in the 5G NOMA system, this paper proposes a power allocation scheme based on the conjugate gradient method, which can maximize the weighted sum rate while ensuring the convergence speed. The simulation results prove the superiority of the performance of this method.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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