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Power Allocation Method of Downlink Non-orthogonal Multiple Access System Based on α Fair Utility Function

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Abstract

The unbalance between system ergodic sum rate and high fairness is one of the key issues affecting the performance of non-orthogonal multiple access (NOMA) system. To solve the problem, this paper proposes a power allocation algorithm to realize the ergodic sum rate maximization of NOMA system. The scheme is mainly achieved by the construction algorithm of fair model based on α fair utility function and the optimal solution algorithm based on the interior point method of penalty function. Aiming at the construction of fair model, the fair target is added to the traditional power allocation model to set the reasonable target function. Simultaneously, the problem of ergodic sum rate and fairness in power allocation is weighed by adjusting the value of α. Aiming at the optimal solution algorithm, the interior point method of penalty function is used to transform the fair objective function with unequal constraints into the unconstrained problem in the feasible domain. Then the optimal solution of the original constrained optimization problem is gradually approximated within the feasible domain. The simulation results show that, compared with NOMA and time division multiple address (TDMA) schemes, the proposed method has larger ergodic sum rate and lower Fairness Index (FI) values.

Keywords

Ergodic Sum Rate, NOMA, Power Allocation, α Fair Utility Function

1. Introduction

The IMT-2020 (5G) promotion group put forward that 5G would make higher requirements for future wireless networks in White Paper on 5G Concept, that is, the rate should reach 0.1 to 1 Gb/s among users, the equipment connection capability should reach $10^2/\mathrm{km}^2$, and the spectrum efficiency is 5 to 15 times higher than the 4G. In order to meet people's growing mobile service demands, there is an urgent need to improve existing multiple access technologies [1]. Against this background, SAITO Y et al. proposed another technology called non-orthogonal multiple access technology.

Non-orthogonal multiple access (NOMA) technology can achieve the balance between system ergodic sum rate and user fairness [2]. By studying some main technologies in the new multiple access technologies, it provides certain theoretical references for the further development of multiple access technologies and promotes the development of mobile communications systems in the future. The NOMA system uses the power multiplexing technology to transmit multiple user signals. The receiver

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achieves correct demodulation of the received signal through serial interference cancellation technology [3]. The traditional orthogonal multiple access (OMA) technology is limited by orthogonal resources and it is difficult to meet the need of the increasing users number. In order to improve the user fairness, generally, the low power is allocated to users with good channel gain and the high power is allocated to those with poor channel gain [4].

Recently, in some NOMA systems series, user fairness issues have received attention [5]. As discussed in [6-8], some fixed power allocation methods are adopted. This scheme implements power allocation using a recursive iteration algorithm, where the recursive attribution is a number greater than zero and less than one. The user with less channel condition will be allocated more power. The difference in power between the two users also depends on the recursive attribution size. These parameters are set by the system and are fixed. It can guarantee that the users with poorer channel gain are allocated more power, but these users with poorer channel conditions may experience poor fairness. In order to improve the user fairness, the cooperation scheme is considered after the downlink of NOMA. For the users in bad condition, the user has strong data forwarding capability, but it will increase the cost of additional channel resources (that is, Special time slot for collaboration). In order to improve user fairness, at the base station side, it is suitable to adopt an appropriate power allocation scheme for the superimposed encoded user information [9]. The maximizing power allocation scheme is adopted in [10] to optimize the instantaneous transmission rate of the signal, so that the minimum value of the signal instantaneous transmission rate is maximized. In order to minimize the occurrence of interrupt events, the interrupt transmission probability is optimized by minimizing the power allocation scheme [11]. In order to improve the fairness, the weight vector is used to adjust the level of fairness [12]. However, the user with the worst channel gain may affect the system throughput, and the weight vector optimization is more challenging. Designing an optimal power allocation scheme is a challenging problem. A proportional fair distribution scheme is adopted in [13,14]. All the users can get the service. The system throughput is high. It is a compromise between user fairness and cell throughput, but the channel state needs to be tracked, and the algorithm complexity is high.

In view of the problems of the above proposed schemes, the preconditions for applying the method in this paper are the channel state information under ideal conditions, and the maximum instantaneous rate and fair utility function to achieve the total throughput maximization power allocation scheme. The proposed method is to adjust the user rate according to the instantaneous channel state information (CSI). Firstly, the optimization problem is transformed into an equivalence problem. Then by setting some parameters to represent a set of user sum rate allocation problems, then constructing a penalty function by the interior point method, and gradually adjusting the penalty factor to solve the extreme point, and then get the optimal solution.

2. System Model and Basic Principle

2.1 NOMA Downlink Signal Model

In the downlink of NOMA system, all the user transmission information in the multiplexed state on the single orthogonal sub-band is linearly superimposed to obtain the sum of the modulated signals. It is shown as follows:

$$x = \sum_{k=1}^{K} \sqrt{p_k} s_k \tag{1}$$

where x is the sum of all modulated signals on the sub-band, K is the total number of users multiplexed on this sub-band, s_k is the modulated information of user k and satisfies $E\left[|s_k|^2\right] = 1$, p_k is the power for user k. The power sum satisfies formula (2), where P is the sum of all powers in the band.

$$\sum_{k=1}^{K} p_k \le P \tag{2}$$

Therefore, the signal y_k obtained by user k in the sub band at the receiving end can be obtained, which is recorded as

$$y_k = h_k \sum_{i=1}^{K} \sqrt{p_i} s_i + n_k, \qquad k \in [1:k] \tag{3}$$

where h_k is the channel gain from the base station to the receiver k on the subcarriers, n_k is the channel noise. Assume that $h_k = d_k^{-\beta/2} g_k$, g_k is a normalized Rayleigh fading channel gain, β is the path fading factor, d_k is the distance between base station and user k, satisfying $d_1 > d_2 > ... > d_k$. Here, the noise is additive white Gaussian noise with zero mean and variance of δ^2. In addition, the user channel gain and noise are independent for each other.

If the base station can get CSI of some terminals, according to the requirement of NOMA power multiplexing, the base station sorts the signals received at the terminal according to the channel gain. If $|h_1|^2 \le |h_2|^2 \le ... \le |h_k|^2$, the power is assigned in the order of $p_1 \ge p_2 \ge ... \ge p_k$. This method can ensure that each terminal user can reliably decode its information [15]. At the receiving end, the serial interference cancellation (SIC) technology is used to accomplish signal decoding. The received signals are ranked according to the signal-to-interference-noise ratio (SINR) or the power from the largest to the smallest. Then, the receiver selects the strongest signal among the undetected signals [16].

The SINR of user signal l decoded at terminal k is

$$\gamma_1 = \frac{p_l H_k}{1 + H_k \sum_{m=l+1}^{K} p_m}, \qquad l \in [1:K] \tag{4}$$

where $H_k = |h_k|^2, \forall k \in [1:K]$. It can be seen that H_k is exponentially distributed, with the meaning of $d_k^{-\beta}$.

According to the SIC principle, the users $\{k+1, K\}$, whose signals are weaker than the user k. They cannot be detected and eliminated. These signals can be considered as noise to the user signal. The rate of user k is as follows

$$R_k(p_k) = \ln\left(1 + \frac{H_k p_k}{1 + H_k \sum_{i=k+1}^{K} p_i}\right), k \in [1:K] \tag{5}$$

2.2 α Fair Utility Function

One of the main purposes of network resource allocation is to achieve the fair distribution of resources among all the users. Usually some fairness assessment methods can be used to measure the fairness of resource allocation. These methods include the max-min fairness criterion and the proportional fairness criterion [17].

This paper uses α fairness to measure the fairness degree. Under the concept of α fairness, the resource allocation is determined by maximizing the constant elasticity of the fair utility function u_α (α is a non-negative parameter) [18]. For the fairness model, the fair utility function is as follows.

$$u_\alpha(x)=\begin{cases}\dfrac{x^{1-\alpha}}{1-\alpha}, for & \alpha\geq 0,\alpha\neq 1\\ \ln(x), for & \alpha=1\end{cases} \tag{6}$$

where x can be data throughput or ergodic rate, $x\in R_+^n$, α is the fairness indicator to achieve multiple fairness among the users and unify the expression of fair resource distribution. When α=0, it means there is no fairness requirement among the users in the cell, $u_\alpha(x)=x$. With the increasing of α, the user fairness also increases. When $\alpha\to\infty$, it means that the users in the cell are absolutely fair.

2.3 Interior Point Method of Penalty Function

The interior point method is used to solve the optimal value of the power allocation under certain restrictions. The interior point method is characterized by defining the constructed unconstrained objective function in a feasible domain [19]. The objective function is defined as

$$\min \quad f(X) \tag{7a}$$

$$s.t. \quad g_u(X)\geq 0 \quad (u=1,2,3,\cdots,m) \tag{7b}$$

For the calculation of the optimization problem, the general expression for the constructed the penalty function is as follows

$$\varphi\left(X,r^{(k)}\right)=f(X)+r^{(k)}\sum_{u=1}^{m}\frac{1}{g_u(X)} \tag{8}$$

or

$$\varphi\left(X,r^{(k)}\right)=f(X)-r^{(k)}\sum_{u=1}^{m}\ln\left[g_u(X)\right] \tag{9}$$

where $r^{(k)}$ is the penalty factor, it is a descending positive sequence, and $\lim_{k\to\infty} r^{(k)}=0$.

The second item of the above penalty function expression is called penalty item or obstacle item. When the iteration point is within the feasible domain, $g_u(X)\geq 0,(u=1,2,3,4,\ldots,m)$. Because $r^{(k)}>0$, the penalty term is positive. When the design point moves from the interior of the feasible region to the constraint boundary, the value of the penalty term increases sharply and tends to infinity. The result is that the value of the penalty function also increases sharply until infinity. So the constraint edge is never touched during the iteration.

3. System Power Allocation Method Based on α Fair Utility Function

The problem of maximizing the ergodic sun rate can be solved by optimizing the power allocation through α fairness. It is about the fair distribution of resources achieved by the user rate *R*, which means that it is the fairness between users.

The optimization goal of the NOMA downlink system is to maximize the α fair utility function that maximizes the ergodic sum rate as the dependent variable

$$\max_{\{p_k\}} \sum_{k=1}^{K} u_\alpha\left[R_k\left(p_k\right)\right] \tag{10a}$$

$$s.t. \quad \sum_{k=1}^{K} p_k \le P \tag{10b}$$

$$p_k \ge 0, k \in [1:K] \tag{10c}$$

where p_k is a real number, and it is an optimized variable of the objective function. Constraint (10b) indicates the constraint condition of maximum allowed transmission power at the base station. Constraint (10c) ensures that all the users on the subcarriers can transmit normally. The maximum ergodic sum rate that satisfies user fairness can be achieved under the above constraint conditions.

The interior point method is introduced to solve the above formula (10a). The interior point method is used to solve the minimum value of the objective function, so the above formulas need to be transformed, which is shown as follows

$$f\left(p_k\right) = \min_{\{p_k\}} -\sum_{k=1}^{K} u_\alpha\left[R_k\left(p_k\right)\right] \tag{11a}$$

$$s.t. \quad \sum_{k=1}^{K} p_k \le P \tag{11b}$$

$$p_k \ge 0, k \in [1:K] \tag{11c}$$

Due to the interference between users, the above problems are non-convex. So, it is difficult to solve the problem directly and obtain the optimal solution. Constructing a penalty function from the above formulas and constraints by using the interior point method can solve this problem.

$$\varphi\left(p_k, r\right) = -\sum_{k=1}^{K} u_\alpha\left[\log_2\left(1 + \frac{H_k p_k}{1 + H_k \sum_{i=k+1}^{K} p_i}\right)\right] \tag{12}$$

According to the property of α fair utility function, there are some different situations.

(1) $\alpha \ge 0, \alpha \ne 1$

The constructed penalty function is

$$\varphi\left(p_k,r\right)=-\sum_{k=1}^{K}\frac{\left(\log_2\left(1+\dfrac{H_k p_k}{1+H_k\sum\limits_{i=k+1}^{K}p_i}\right)\right)^{1-\alpha}}{1-\alpha}-r\ln\left[P-\sum_{i=1}^{K}p_i\right] \tag{13}$$

By taking the derivative of p_k for formula (13), it can get the formula (14)

$$\begin{aligned}\frac{\partial\varphi}{\partial p_k}=&-\left[\log_2\left(1+\frac{H_k p_k}{1+H_k\sum\limits_{i=k+1}^{K}p_i}\right)\right]^{-\alpha}\frac{H_k}{\left(1+H_k\sum\limits_{i=k}^{K}p_i\right)\ln 2}+\sum_{m=1}^{k-1}\left\{\left[\log_2\left(1+\frac{H_m p_m}{1+H_m\sum\limits_{i=m+1}^{K}p_i}\right)\right]^{-\alpha}\frac{p_m H_m H_m}{\left(1+H_m\sum\limits_{i=m}^{K}p_i\right)\left(1+H_m\sum\limits_{i=m+1}^{K}p_i\right)\ln 2}\right\}\\&+\frac{r}{P-\sum\limits_{i=1}^{K}p_i}\qquad k\neq 1\end{aligned} \tag{14}$$

When $k=1$, p_1 is the power allocated for the first user signal, the partial derivative is

$$\frac{\partial\varphi}{\partial p_1}=-\left[\log_2\left(1+\frac{H_1 p_1}{1+H_1\sum\limits_{i=2}^{K}p_i}\right)\right]^{-\alpha}\frac{H_1}{\left(1+H_1\sum\limits_{i=1}^{K}p_i\right)\ln 2}+\frac{r}{P-\sum\limits_{i=1}^{K}p_i}\qquad k=1 \tag{15}$$

Simplify formula (14) to get formula (16)

$$\frac{\partial\varphi}{\partial p_k}=-\left[\log_2\left(1+\frac{H_k p_k}{1+H_k\sum\limits_{i=k+1}^{K}p_i}\right)\right]^{-\alpha}\frac{H_k}{\left(1+H_k\sum\limits_{i=k}^{K}p_i\right)\ln 2}+\left[\log_2\left(1+\frac{H_{k-1}p_{k-1}}{1+H_{k-1}\sum\limits_{i=k}^{K}p_i}\right)\right]^{-\alpha}\frac{H_{k-1}}{\left(1+H_{k-1}\sum\limits_{i=k-1}^{K}p_i\right)\ln 2}+\frac{\partial\varphi}{\partial p_{k-1}} \tag{16}$$

From the above, when the allocated power is infinitely close to the total power of the sub-band, the objective function can get the optimal solution, which satisfies with

$$P-\sum_{i=1}^{K}p_i=\eta \tag{17}$$

where η is the difference between the specified power and the allocated power. Formula (18) can be obtained to make the partial derivative equal to zero.

$$\frac{\partial\varphi}{\partial p_k}=0,k=1,2,\cdots,K \tag{18}$$

Substituting Eq. (17) into Eq. (15), the power expression p_1^* for the first user can be obtained.

$$p_1^* = \frac{1+H_1\left(P-\eta\right)}{H_1}\left(1-\frac{1}{2^{\sqrt[\alpha]{\frac{\eta H_1}{r\ln 2\left[1+H_1\left(P-\eta\right)\right]}}}}\right) \tag{19}$$

Substituting (19) and (18) into $\frac{\partial\varphi}{\partial p_2}=0$, the power expression p_2^* for the second user can be obtained.

$$p_2^* = \frac{1+H_2\left(P-\eta-p_1\right)}{H_2}\left(1-\frac{1}{2^{\sqrt[\alpha]{\frac{\varepsilon H_2}{r\ln 2\left[1+H_2\left(P-\eta-p_1\right)\right]}}}}\right) \tag{20}$$

By repeating the above steps, the method sequentially obtains the power allocation scheme for user 3, user 4, … , user K in turn. This is also the decoding order for the NOMA receiver. So, the power allocation scheme can be defined as

$$p_k^* = \frac{1+H_k\left(P-\eta-\sum_{i=1}^{k-1}p_i\right)}{H_\mathrm{k}}\left(1-\frac{1}{2^{\sqrt[\alpha]{\frac{\eta H_k}{r\ln 2\left[1+H_k\left(P-\eta-\sum_{i=1}^{k-1}p_i\right)\right]}}}}\right) \tag{21}$$

(2) $\alpha=1$

Through the same method, the user power expression can be solve. The constructed penalty function is

$$\varphi\left(p_k,r\right) = -\sum_{k=1}^{K}\ln\left(\log_2\left(1+\frac{H_k p_k}{1+H_k\sum_{i=k+1}^{K}p_i}\right)\right)-r\ln\left[P-\sum_{i=1}^{K}p_i\right] \tag{22}$$

In the same way, taking the derivative of p_k for formula (22), the power expression for the user k can be obtained as formula (23).

$$p_k^* = \frac{1+H_k\left(P-\eta-\sum_{i=1}^{k-1}p_i\right)}{H_k}\left(1-\frac{1}{2^{\frac{\eta H_k}{r\ln 2\left[1+H_k\left(P-\varepsilon-\sum_{i=1}^{k-1}p_i\right)\right]}}}\right) \tag{23}$$

From p_k^* expression formula, the optimal solution of the objective function under the condition of fixed α can be calculated by the following steps.

Algorithm. Calculate the optimal solution for a fixed α

```
Initialize C, $\varepsilon$ ,t=1, $r^1$, $p_k(r^1), \forall k \in [1:K]$
Calculate $\min \varphi[p_k(r^1), r^1]$
while ( $\left|\frac{\varphi[p_k(r^t), r^t] - \varphi[p_k(r^{t-1}), r^{t-1}]}{\varphi[p_k(r^{t-1}), r^{t-1}]}\right| > \varepsilon$ ) do
    set $r^{t+1} = Cr^t$ , $t=t+1$
    Calculate $p_k(r^t)$, $\min \varphi[p_k(r^t), r^t]$
until $\left|\frac{\varphi(p_k^t, r^t) - \varphi(p_k^{t-1}, r^{t-1})}{\varphi(p_k^{t-1}, r^{t-1})}\right| \le \varepsilon$
$p_k^* \leftarrow p_k(r^t), f(p_k^*) \leftarrow f[p_k^*(r^t)]$
```

where C is the reduction factor of the penalty factor, ε is the convergence accuracy, t is the iteration number. The initial penalty factor $r^1 > 0$, $\varepsilon > 0$. The initial point in the feasible domain is $p_k(r^1)$. As $t=1$, construct the penalty function $\varphi[p_k(r^t), r^t]$. Starting from point p_k^t , the unconstrained optimization method is used to solve the extreme point $p_k(r^t)$ of the penalty function $\varphi[p_k(r^t), r^t]$. If $\left|\frac{\varphi(p_k^t, r^t) - \varphi(p_k^{t-1}, r^{t-1})}{\varphi(p_k^{t-1}, r^{t-1})}\right| \le \varepsilon$ is satisfied, The algorithm stops iterative calculation and uses $p_k(r^t)$ as the optimal solution of the function $f(p_k)$. Otherwise, it takes $r^{t+1} = Cr^t$, $t=t+1$, and continues to calculate until the termination condition is satisfied.

4. Simulation Results and Analysis

To assess quantitative fairness, a widely used Fairness Index (FI) is defined as

$$FI(R_k) = \left(\sum_{k=1}^{K} R_k\right)^2 \Big/ K\left(\sum_{k=1}^{K} R_k^{\,2}\right) \tag{24}$$

The *FI* can be any value within the interval $[1/K, 1]$. The greater the *FI* value is, the higher the fairness level is. When *FI*=1, it means that the users in the cell are absolutely fair. When *FI*→0, it means that the users are completely unfair.

Assumed the large-scale fade gain is Rayleigh distributed, which is $gi \sim CN(0,1)$. The user noise is an additive white Gaussian variable with the zero mean and unit variance. The distance between the base station and user *k* is $d_k = 1.5^{K-k}$. The path loss index is 2, which reflects the good propagation conditions.

Fig. 1 shows the relation between ergodic sum rate and SINR for TDMA and NOMA system at different α values, where the user number is 5. Fig. 1 shows that as the SNR increases, the system ergodic sum rate increases. Under the same conditions, the ergodic sum rate of the NOMA system is better than that of TDMA system. When *α*=5, the system performance is the best, and the ergodic sum rate of the NOMA system is increased by 49.9% compared to the TDMA system.

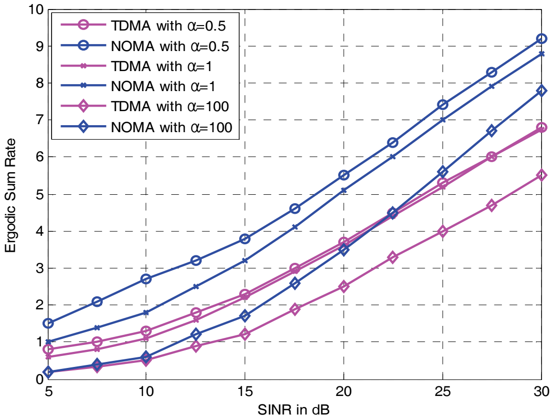

Fig. 1. The relation between ergodic sum rate and SINR for TDMA and NOMA system.

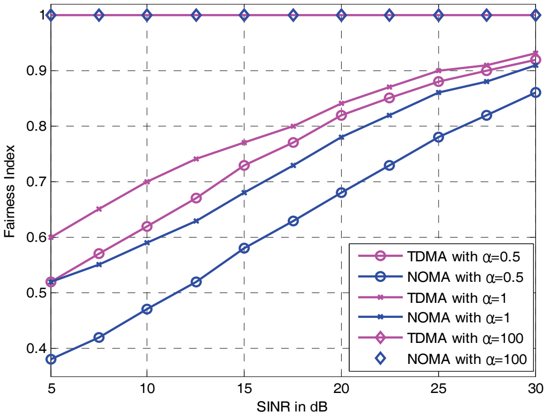

Fig. 2. The relation between FI and SINR for TDMA and NOMA system.

Fig. 2 shows the relation between Fairness Index and SINR for TDMA and NOMA system at different *α* values, where the user number is 5. Fig. 2 shows that as the SNR increases, the system FI of TDMA and NOMA also increases. Under the same conditions, the TDMA system FI value is superior to the NOMA system. The larger *α* is, the more fair the system is.

Table 1 shows the difference about the system ergodic sum rate and FI between NOMA system and TDMA system under different *α* values.

Table 1. Comparison of NOMA and TDMA system under different *α* values

	***α*=0.5**	***α*=1**	***α*=100**
Improvement of the ergodic sum rate of NOMA compared with that of TDMA (%)	49.9	38.8	38.9
Improvement of the TDMA FI compared with that of NOMA (%)	20.1	9.6	0

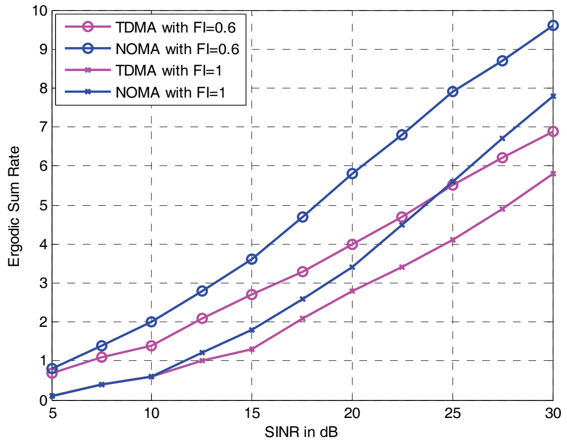

Fig. 3. Ergodic sum rate vs SINR in dB, where k = 5, FI = 0.6 and 1.

In order to compare the NOMA and TDMA solutions fairly, Fig. 3 shows the relation between ergodic sum rate and SNR for TDMA and NOMA system at different FI values, where the user number is 5. Fig. 3 shows that as the SINR increases, the system ergodic sum rate of TDMA and NOMA increases. Under the same conditions, the ergodic sum rate of the NOMA system is significantly better than that of TDMA system. When FI=0.6, the system performance is the best, and the ergodic sum rate of the NOMA system is increased by 40.2% compared to the TDMA system.

Fig. 4 shows the relation between ergodic sum rate and FI for TDMA and NOMA system at different user values, where SINR=20dB. The detailed results are shown in Table 2.

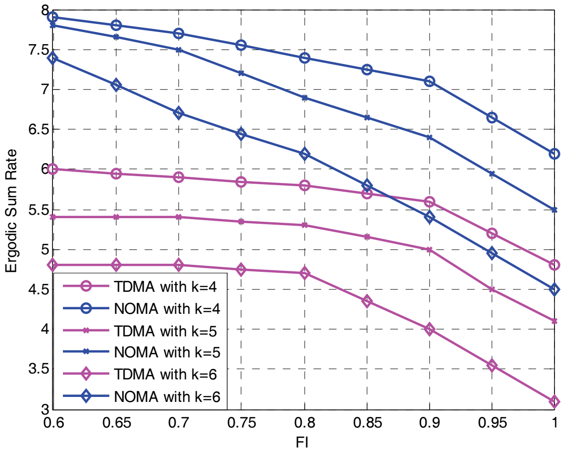

Fig. 4. Ergodic sum rate vs FI, where SINR = 20 dB, and k = 4, 5, and 6.

Table 2. Comparison of NOMA and TDMA system under different user numbers

	k = 4	**k = 5**	**k = 6**
Improvement of the ergodic sum rate of NOMA compared with that of TDMA (%)	29.04	34.98	40.15

Fig. 4 and Table 2 show that the ergodic sum rate of TDMA and NOMA decreases as the FI value increases. Under the same conditions, the NOMA system ergodic sum rate is superior to the TDMA system. As shown in Figs. 3 and 4, it can be seen that NOMA provides a significant increase in ergodic sum rate performance over the TDMA scheme at the same required level of fairness.

5. Conclusion

For the NOMA power allocation part, a power allocation method based on α fairness to achieve the maximum ergodic sum rate is proposed. The computational complexity is reduced evidently by penalty function interior point method. It approaches the solution of objective function within the feasible region. This scheme proves the superiority of fair utility function under a single antenna and optimizes the ergodic sum rate under the condition of satisfying fairness among users. This approach achieves user fairness and maximizes ergodic sum rate balance. The numerical results show that compared with the NOMA and TDMA methods using this method, the performance of NOMA is obviously better than that of TDMA. For example, when α=0.5, the average ergodic sum rate of NOMA is increased by 49.9% compared with TDMA. When FI=1, the average ergodic sum rate increased by 31% compared with TDMA.

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