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다중-셀 네트워크를 위한 비-직교 다중접속의 전력 최적화

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Power Optimization of NOMA for Multi-Cell Networks

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요 약

비 직교 다중 접속 기술(Non-orthogonal multiple access, NOMA)은 차세대 무선 통신에서 데이터율 및 주파수 효율에 대한 요구를 충족하기 위한 기술로 고려된다. 본 논문에서는 NOMA의 2개 셀 다운링크 통신 시나리오를 수행하는 방법에 대해 연구한다. 인접한 셀의 데이터 전송은 서로 간섭으로서 작용하며, 각 셀은 두 명의 사용자로 구성된다. 다음으로, NOMA 사용자 간의 전력할당 최적화에 관한 문제를 수식화 한다. 이 최적화 문제는 두 가지 조건하에서 시스템 처리량을 최대화 하는 것을 목표로 한다. 첫 번째는, NOMA 사용자 디바이스들 간에 전력을 분배하기 위한 전체 송신전력 제한에 대해 고려한다. 두 번째는, 사용자의 최저 데이터 속도 요구조건을 충족하기 위한 서비스 품질 요구 제한에 대해 고려한다. 제안된 최적화 문제에 기반한 두 개의 다른 닫힌 형식의 해를 유도한다. 제안된 전력 할당 기법의 성능은 시뮬레이션 결과를 통해 증명한다.

Key Words : Non-orthogonal multiple access, multi-cell network, inter-cell interference, power optimization, capacity

ABSTRACT

Non-orthogonal multiple access (NOMA) is thought of as a challenging technique for providing the data rate and spectral efficiency requirement in the era of future wireless communication. This article studies the performance of a NOMA adopted two-cell downlink communication scenario where adjacent cells interfere into each other's data transmission and each cell consists of two users. Then, the optimization problem with respect to power allocation between NOMA users is formulated. This optimization problem aims at maximizing the throughput of the system under two constraints. First, it considers a total transmit power constraint for distributing power among NOMA user devices. Second, it regards a quality-of-service demand constraint to meet minimum data rate requirements of the users. Two different closed-form solutions are derived based on the proposed optimization problem. The superiority of the proposed power allocation scheme is proved through simulation results.

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Ⅰ. Introduction

Non-orthogonal multiple access (NOMA) technique with successive interference cancellation (SIC) receiver at the near user is considered as one of the most competitive candidates to fulfill the demand of upcoming future wireless networks. It facilitates multiple users to share the same time and frequency by power domain multiplexing and provides a superior spectral efficiency as well as improved throughput performance by doing superposition of the radiated signals. The flexibility of sharing same resource (time, frequency and code) by NOMA has made it superior over conventional multiple access systems[1-4].

Nonetheless, NOMA requires efficient power allocation (PA) at the transmitter side so to ascertain minimum quality of service (QoS) and target data rates of both far and near users. Because of the much importance of optimum PA in NOMA, recently, many researchers are focusing on this area of exploration for both single input single output and multiple input multiple output cases[5-12]. Different PA techniques for downlink NOMA scheme were proposed in [5] and [6] to maximize the capacity under a total transmit power constraint and minimum rate requirements. Again, by considering the outage probabilistic constraints and the optimal decoding order, two optimization problems of transmit power and user fairness under availability of average channel state information for NOMA systems were discussed in [7]. Further, impact on maximum weighted sum rate was investigated by considering optimal power allocation approach and greedy-search-based user pairing and selection in [9] and [10] respectively. In [11], superiority of performance of NOMA system based on the proposed power allocation scheme over orthogonal multiple access (OMA) was shown for a network consisting of multiple user devices within the cell. All of the contributions mentioned above focused on the performance analysis of single cell scenario consisting of two users. Hence, to draw a more practical scenario, authors of [12] give importance on the power control for NOMA system with two interfering cells. They studied the performance of NOMA system over Rayleigh fading channel based on Yates's power control framework wherein negligible inter-cell interference was considered. The study showed that the NOMA system noticeably outperforms some power-controlled OMA schemes.

Unlike the existing works in the literature, a downlink NOMA multi-cell network is proposed in this paper. A brief description of the contribution is enumerated as follows.

- A downlink NOMA protocol with two interfering cells over Rayleigh fading channel is investigated where intra-cell as well as inter-cell interference (ICI) are considered.
- Power distribution between two users is optimized by applying the Karush-Kuhn-Tucker (KKT) conditions to the system under total power constraint and minimum data rate requirements of both users to ensure a QoS.
- By taking intra-cell and inter-cell interferences into account, the influence of interferences on the performance of the proposed system is explored.
- Finally, the performance of the proposed NOMA protocol under the optimal power allocation is compared with the performance under fixed power allocation strategy.

In the rest of the paper, system model, capacity analysis, power optimization, numerical results, and conclusion are described in section II, III, IV, V and VI, respectively.

Ⅱ. System Model

In this study, a NOMA-based system with two interfering cells (e.g., Cell1, Cell2) is considered as shown in Fig. 1. Each cell consists of one base station (BS) and two users. NUi and FUi refer to the near and far user of the celli respectively, where i=1, 2.

Consider all the links are subjected to Rayleigh fading channel with additive white Gaussian noise (AWGN) at the receiver. Channel coefficients of the near and far user's channel from their respective BSi are respectively represented by $g_{ni} \sim CN(0, \lambda_{ni} = d_{ni}^{-v})$

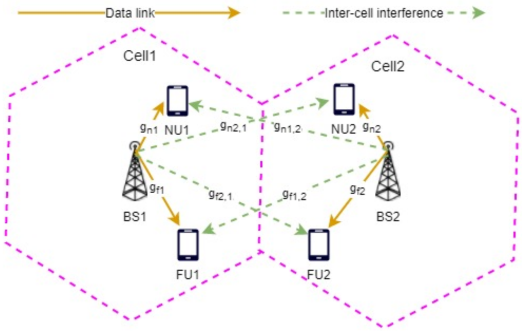

Fig. 1. A downlink NOMA system with two interfering cells.

with zero mean and λ_{ni} variance and $g_{fi} \sim CN(0, \lambda_{fi} = d_{fi}^{-v})$ with zero mean and λ_{ti} variance. In addition, $g_{fi,j} \sim CN(0, \lambda_{fi,j} = d_{fi,j}^{-v})$ with zero mean and variance $\lambda_{fi,j}$ and $g_{ni,j} \sim CN(0, \lambda_{ni,j} = d_{ni,j}^{-v})$ with zero mean and variance $\lambda_{ni,j}$ respectively denote the channel coefficients of far and near user of BSi from BSj, where j=1, 2 and i≠j. Parameters d_{ni}, d_{fi}, $d_{fi,j}$, and $d_{ni,j}$ respectively represent the distance in meters from BSi to NUi, BSi to FUi, BSj to FUi, and BSj to NUi; i≠j. The path loss exponent is denoted by v.

All channels are subjected to the Rayleigh fading. So, the channel gain $|g_{x,y}|^2$ follows the exponential distribution with mean $\lambda_{x,y}$[3]. Based on considering $d_{n1} < d_{f1} < d_{f1,2} < d_{n1,2}$ and $d_{n2} < d_{f2} < d_{f2,1} < d_{n2,1}$, it can be respectively assumed by without loss of generality that $\lambda_{n1} < \lambda_{f1} < \lambda_{f1,2} < \lambda_{n1,2}$ and $\lambda_{n2} < \lambda_{f2} < \lambda_{f2,1} < \lambda_{n2,1}$. The power allocation factors for near and far users of Cell1 are represented by δ and $(1-\delta)$ respectively, where $\delta + (1-\delta) = 1$. In addition, the power allocation factors for near and far user of Cell2 are respectively represented by q and $(1-q)$, where $q + (1-q) = 1$. According to the NOMA literature [1-4], more power needs to be assigned with the transmitted symbols for the far user because of worse channel condition. On the other hand, less power is assigned with the transmitted symbols for the near user due to having better channel condition.

In the considered protocol, both BS simultaneously transmit the data to their intended users (e.g., NU1 and FU1 from BS1; NU2 and FU2 from BS2) through the same frequency band by following the law of NOMA downlink transmission.

BS1 transmits $\sqrt{\delta p_t}\, x_{n1} + \sqrt{(1-\delta) p_t}\, x_{f1}$ signal to the NU1 and FU1 wherein p_t is the total transmit power of the BS1 and $\delta < (1-\delta)$. At the same time of BS1's transmission, BS2 also transmits it's signal $\sqrt{q p_{tt}}\, x_{n2} + \sqrt{(1-q) p_{tt}}\, x_{f2}$ to NU2 and FU2 wherein p_{tt} is the total transmit power of the BS2 and $q < (1-q)$. Because of being adjacent cell and the changing behavior of the wireless channel, the transmission of data in cell2 interferes into the transmission of data in cell1 and vice versa.

Ⅲ. Capacity Analysis

According to the principle of downlink NOMA, NU1 first decodes the FU1's data by treating its own data as noise. Then, by following SIC strategy, NU1 subtracts the decoded information from the received signal to extract its own information. During this process the signal from the BS2 is regarded as noise by NU1. Therefore, the achievable data rate of near user at Cell1 is expressed as follows.

$$R_{NU1} = \beta \log_2\left(1 + \frac{\delta\rho |g_{n1}|^2}{|g_{n1,2}|^2 \gamma + 1}\right) \qquad (1)$$

Where $\rho = {}^{p_t}\!/_{\sigma^2}$ is the transmit signal to noise ratio (SNR) of Cell1, $\gamma = {}^{p_{tt}}\!/_{\sigma^2}$ is the transmit SNR of Cell2, σ^2 is the variance of AWGN, and β is the total bandwidth of the system. As the signal strength of NU1 gets decreased at FU1, FU1 decodes its information by considering NU1's signal as well as signal from BS2 as noise. So, the achievable data rate of far user at Cell1 is given by

$$R_{FU1} = \beta \log_2\left(1 + \frac{(1-\delta)\rho |g_{f1}|^2}{\delta\rho |g_{f1}|^2 + |g_{f1,2}|^2 \gamma + 1}\right) \qquad (2)$$

The sum capacity of Cell1 is therefore represented by

$$R_{cell1} = R_{NU1} + R_{FU1} \tag{3}$$

By adopting the same principle as described for NU1 and FU1 at Cell1, the NU2 and FU2 of Cell2 also decode their data. So, the achievable data rates of near and far user at Cell2 are derived as follows:

$$R_{NU2} = \beta \log_2\left(1 + \frac{q\gamma |\, g_{n2}|^2}{|\, g_{n2,1}|^2 \rho + 1}\right) \tag{4}$$

$$R_{FU2} = \beta \log_2\left(1 + \frac{(1-q)\gamma |\, g_{f2}|^2}{q\gamma |\, g_{f2}|^2 + |\, g_{f2,1}|^2 \rho + 1}\right) \tag{5}$$

Therefore, the sum capacity of Cell2 is given by

$$R_{cell2} = R_{NU2} + R_{FU2} \tag{6}$$

Moreover, the overall sum capacity of the system can be expressed as follows:

$$R_{total} = R_{cell} + R_{cell2} \tag{7}$$

Ⅳ. Power Optimization

Efficient power allocation in NOMA is off high importance to obtain the maximum benefit from the protocol. In this research, the optimization of power allocation focuses on maximum throughput under a total power constraint and the minimum rate requirements of the users to maintain a certain level of QoS. The optimization problem for Cell1 can be expressed by using following formula.

$$\begin{aligned} &Maximize && R_{cell} \\ &Subject\ to && \delta + (1-\delta) = 1 \\ &&& (1-\delta) > \delta \\ &&& \delta > 0,\ (1-\delta) > 0 \\ &&& R_{FU1} \geq R_t \\ &&& R_{NU1} \geq R_{\min} \end{aligned} \tag{8}$$

Where, R_t and $R_{\min}$ are the minimum target data rates of the far user and near user respectively. The first constraint refers to that the sum of the power allocation coefficients should be unity so to make the sum of allocated powers between users equal to the total transmit power. The second constraint expresses that the power allocation coefficient for the far user must be higher than that of the near user. The third constraint depicts that each of the power allocation coefficients must be kept at a value that is higher than zero. The fourth and fifth constraints respectively assure the minimum rate requirement of FU1 and NU1. If $\beta = 1$ and $\rho = \gamma$ are considered, eq. (3) can be written as

$$\begin{aligned} R_{cell1} &= \log_2\left(1 + \frac{\delta\rho |\, g_{n1}|^2}{|\, g_{n1,2}|^2 \rho + 1}\right) + \\ &\quad \log_2\left(1 + \frac{(1-\delta)\rho |\, g_{f1}|^2}{\delta\rho |\, g_{f1}|^2 + |\, g_{f1,2}|^2 \rho + 1}\right) \\ &= \log_2\left\{\left(1 + \frac{\delta\rho\lambda_{n1}}{\lambda_{n1,2}\rho + 1}\right)\left(1 + \frac{(1-\delta)\rho\lambda_{f1}}{\delta\rho\lambda_{f1} + \lambda_{f1,2}\rho + 1}\right)\right\} \\ &= \log_2\left\{1 + \frac{A + B + C}{(\lambda_{n1,2}\rho + 1)(\delta\rho\lambda_{f1} + \lambda_{f1,2}\rho + 1)}\right\} \\ &= \log_2\{1 + f(\delta)\} \end{aligned}$$

where, $A = \delta\rho^2(\lambda_{n1}\lambda_{f1,2} + \lambda_{n1}\lambda_{f1} - \lambda_{n1,2}\lambda_{f1})$, $B = \delta\rho(\lambda_{n1} - \lambda_{f1})$, $C = \rho\lambda_{f1}(1 + \rho\lambda_{n1,2})$. The optimization problem of (8) can be written as

$$\begin{aligned} &Maximize\ \ f(\delta) \\ &Subject\ to \\ &\left(\frac{\lambda_{n1,2}\rho + 1}{\rho\lambda_{n1}}\right)^{-1} R_{\min}^{*} \leq \delta \leq \frac{\rho\lambda_{f1} - R_t^{*}\rho\lambda_{f1,2} - R_t^{*}}{(1 + R_t^{*})\rho\lambda_{f1}} \end{aligned} \tag{9}$$

where, $R_t^{*} = 2^{R_t} - 1$ and $R_{\min}^{*} = 2^{R_{\min}} - 1$.

At first, the optimal solution is derived for meeting the far user's minimum data rate demand. After meeting R_t, the remaining power will be used to maximize the system's overall throughput. Derivation of the constraint of δ for meeting the minimum rate requirement of the far user,

$$\begin{aligned} &R_{FU1} \geq R_t \\ &R_t \leq \log_2\left(1 + \frac{(1-\delta)\rho\lambda_{f1}}{\delta\rho\lambda_{f1} + \lambda_{f1,2}\rho + 1}\right) \\ &2_t^R - 1 \leq \frac{(1-\delta)\rho\lambda_{f1}}{\delta\rho\lambda_{f1} + \lambda_{f1}\rho + 1} \end{aligned}$$

$$R_t^* \leq \frac{(1-\delta)\rho\lambda_{f1}}{\delta\rho\lambda_{f1}+\lambda_{f1,2}\rho+1} \tag{10}$$

After some simplification, (10) can be reformed as

$$\delta \leq \frac{\rho\lambda_{f1}-R_t^*\lambda_{f1,2}\rho-R_t^*}{(1+R_t^*)\rho\lambda_{f1}} \tag{11}$$

In practical case, it may be also required to meet the near user's minimum rate demand and use the remaining power to boost up system's capacity. Derivation of the constraint of δ for meeting the minimum data rate requirement of near user,

$$\begin{aligned} &R_{NU1} \geq R_{\min} \\ &R_{\min} \leq \log_2\left(1+\frac{\delta\rho\lambda_{n1}}{\lambda_{n1,2}\rho+1}\right) \\ &2_{\min}^{R}-1 \leq \frac{\delta\rho\lambda_{n1}}{\lambda_{n1,2}\rho+1} \\ &(\lambda_{n1,2}\rho+1)R_{\min}^* \leq \delta\rho\lambda_{n1} \end{aligned} \tag{12}$$

After some modification, (12) can be reformed as

$$\delta \geq \frac{(\lambda_{n1,2}\rho+1)R_{\min}^*}{\rho\lambda_{n1}} \tag{13}$$

The Lagrange function of the optimization problem of (9) can be expressed as

$$\begin{aligned} F=f(\delta)+&\left\{\delta-\frac{\rho\lambda_{f1}-R_t^*\lambda_{f1,2}\rho-R_t^*}{(1+R_t^*)\rho\lambda_{f1}}\right\}+ \\ &\left\{\frac{(\lambda_{n1,2}\rho+1)R_{\min}^*}{\rho\lambda_{n1}}-\delta\right\}\lambda_2 \end{aligned} \tag{14}$$

where λ_1 and λ_2 are the Lagrange multipliers for the constraints $R_t \leq R_{FU1}$ and $R_{\min} \leq R_{N1}$ respectively. By applying the KKT conditions to (9), the optimization problem can be solved as

$$\frac{dF}{d\delta}=0 \tag{15}$$

$$\lambda_1\left\{\delta-\frac{\rho\lambda_{f1}-R_t^*\lambda_{f1,2}\rho-R_t^*}{(1+R_t^*)\rho\lambda_{f1}}\right\}=0 \tag{16}$$

$$\lambda_2\left\{\frac{(\lambda_{n1,2}\rho+1)R_{\min}^*}{\rho\lambda_{n1}}-\delta\right\}=0 \tag{17}$$

$$\delta-\frac{\rho\lambda_{f1}-R_t^*\lambda_{f1,2}\rho-R_t^*}{(1+R_t^*)\rho\lambda_{f1}} \leq 0 \tag{18}$$

$$\frac{(\lambda_{n1,2}\rho+1)R_{\min}^*}{\rho\lambda_{n1}}-\delta \leq 0 \tag{19}$$

$$\lambda_{1,}\ \lambda_2 > 0 \tag{20}$$

$$0 < \delta < \frac{1}{2} \tag{21}$$

To derive the power allocation factor δ, both of the KKT conditions of (16) and (17) must be satisfied with the constraints $\lambda > 0$ and $\lambda_2 > 0$.

The optimal value of δ (represented as δ_{F1}^*) can be obtained from (16) under the conditions of $\lambda_1 > 0$ and $\lambda_2 = 0$ as given below:

$$\delta_{F1}^* = \frac{\rho\lambda_{f1}-R_t^*\lambda_{f1,2}\rho-R_t^*}{(1+R_t^*)\rho\lambda_{f1}} \tag{22}$$

Again, the optimal value of δ (represented as δ_{N1}^*) can be obtained from (17) under the conditions of $\lambda_2 > 0$ and $\lambda_1 > 0$ as expressed below:

$$\delta_{N1}^* = \frac{(\lambda_{n1,2}\rho+1)R_{\min}^*}{\rho\lambda_{n1}} \tag{23}$$

Similarly, the optimal values of power allocation factors for meeting the minimum data rate demands of far and near users of Cell2 can also be derived by applying KKT conditions as applied for Cell1's FU1 and NU1 respectively.

Ⅴ. Numerical Results

The simulation results to measure the performance of the proposed power allocation scheme for the suggested NOMA protocol are demonstrated in this section. As both cells are considered identical, all simulations are conducted for Cell1 and overall capacity of the system is simply the sum of both cells capacities. Performances are evaluated under the average of 10^5 channel realizations, path-loss exponent $v=3$, and the normalized distances $d_{f1}=1$ and $d_{n1}=0.5$. In all figures, Perf. stands for perfect, Imp. refers to imperfect, and $R_{Sum}=R_{Cell1}$.

Fig. 2. depicts both of the individual user's capacity and the sum capacity of the considered protocol across different SNR values. All plots are shown under optimal power allocation for meeting far user's minimum data rate, $R_t=1$. This is why R_{FU1} remains same irrespective of the ICI values, i.e., It shows unit data rate at normalized $d_{f1,2}=\infty$, $d_{f1,2}=3.25$, and $d_{f1,2}=1.25$. On the other hand, data rates of R_{NU1} and R_{Sum} increase with the less interference from Cell2. Hence, it is clear from figure that the ICI has a negative impact on the performance of the NOMA system; the capacity becomes better for less ICI and the best throughput has been achieved by total cancellation of ICI.

Fig. 3. also refers to both of the individual user's capacity and the sum capacity of the considered protocol across different SNR values but under the optimal allocated power to meet the near user's minimum data rate, $R_{\min}=1$. So, R_{NU1} exhibits same value irrespective of the distance between NU1 and BS2, i.e., It achieves unit data rate at normalized distances $d_{n1,2}=\infty, d_{n1,2}=3.75$, and $d_{n1,2}=1.75$. On the contrary, data rates of R_{FU1} and R_{Sum} increase with the increase of distances of $d_{f1,2}$ and $d_{n1,2}$. The adverse effect of ICI on the performance of the proposed protocol is identified for this case too. One more finding is that the sum throughput of the system here is less than the sum capacity of Fig. 1. So, it has been concluded that the specific data rate of the proposed system is less under the optimal power allocation targeting $R_{\min}=1$ than optimal power allocation targeting $R_t=1$. In Fig. 3., it results so because of interruption by ICI as well as interference from near user data during the calculation of sum throughput.

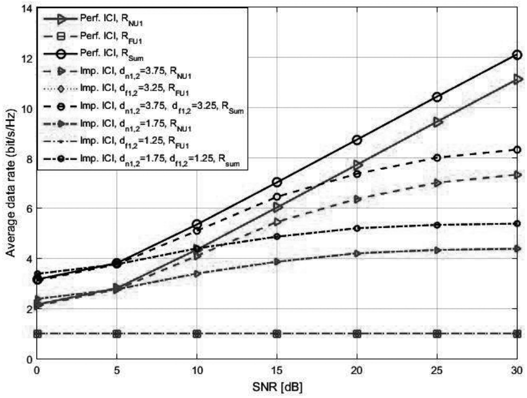

Fig. 2. Average data rate versus SNR of Cell1 under the optimal power allocation for meeting minimum far user data rate

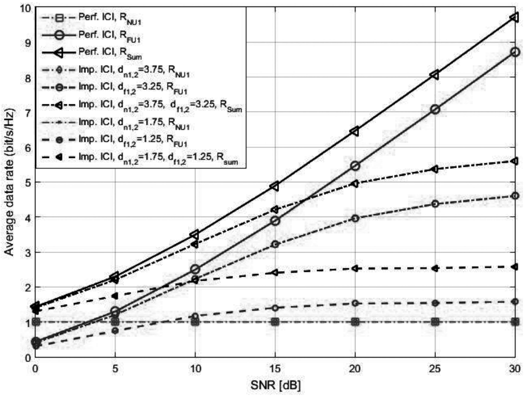

Fig. 3. Average data rate versus SNR of Cell1 under the optimal power allocation for meeting minimum near user data rate

Fig. 4. shows the sum capacity across different SNR values of Cell1 in considered protocol under optimal power allocation to meet $R_t=1$ and under fixed power allocation. In this plot, two cases are shown, i.e., one is for no ICI and another one is for a certain value of ICI. Two values (e.g., $\delta=0.3$ and $\delta=0.5$) of fixed power allocation for the near user are used to investigate the performance and compared with the performance under the optimal power value. In both cases of ICI values, the sum capacity under the proposed optimal power allocation strategy is superior over fixed power allocation strategy.

Fig. 5. compares the sum capacity vs SNR performance under optimal power allocation for meeting minimum near user data rate and under fixed power allocation. Perfect ICI has been considered for all plots. It is clear from the figure

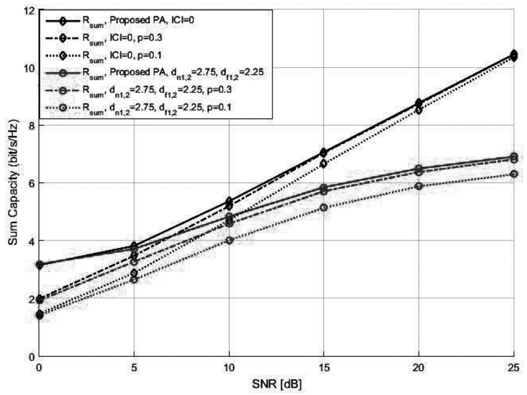

Fig. 4. Sum capacity versus SNR of Cell1 under optimal power for minimum far user data rate and fixed power allocation strategy

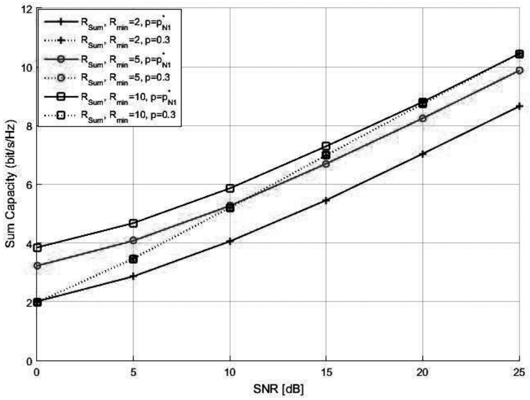

Fig. 5. Sum capacity versus SNR of Cell1 for different minimum near user data rate under optimal power and fixed power allocation strategy

that the throughput under δ_{N1}^{*} is not superior over fixed power allocation (e.g., $\delta = 0.3$) at every case; different as shown in previous figure under δ_{F1}^{*}. If $R_{\min} = 2$ is set, then R_{Sum} under δ_{N1}^{*} is less than R_{Sum} under $\delta = 0.3$ for whole of the considered SNR range. If $R_{\min} = 5$ is set, then R_{Sum} under δ_{N1}^{*} is higher than R_{Sum} under $\delta = 0.3$ at low SNR but lower at high SNR. Lastly, R_{Sum} under δ_{N1}^{*} attains higher value than R_{Sum} under $\delta = 0.3$ at all SNR by setting up $R_{\min} = 10$. So, for the considered SNR range, $R_{\min} = 10$ is the trade-off of the minimum near user data rate to achieve better capacity by using optimal power allocation δ_{N1}^{*}.

Ⅵ. Conclusion

In this study, a new power allocation strategy for two-cell downlink NOMA scenario has been investigated to maximize the sum capacity of the system under a total transmit power constraint and the minimum data rate demands of both far and near users of a specific cell. Two closed-form solutions of the optimal power allocation have been derived; one is based on meeting the minimum data rate requirement of far user and the remaining one is based on fulfilling the minimum data rate requirement of near user. Simulation results have proved the superiority of the proposed optimal power allocation strategy over fixed power allocation strategy. The adverse effect of ICI on the capacity performance of NOMA scheme in a two-cell network also has been investigated. Hence, finding out the perfect ICI cancellation method in NOMA multi-cell protocol and power optimization for multi-user instead of two users in each cell is kept for the future research.

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