Power Allocation Based on SINR Balancing for NOMA Systems with Imperfect Channel Estimation

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Abstract—This paper investigates power allocation for a downlink non-orthogonal multiple access (NOMA) system with a base station and two users under imperfect channel estimation, where the variance of the channel estimation error for each transmission link is assumed to be known. We first present approximated user capacity expressions according to the error variance information, and then formulate a power allocation optimization problem between the two users for maximizing the minimum approximated user capacity under a total power constraint. Since such a max-min problem is equivalent to maximizing the minimum approximated received signal-to-interference-plus-noise ratio (SINR), a closed-form power allocation solution can be derived based on SINR balancing between the two users. The proposed method involves solving a quadratic equation, and only low implementation complexity is required for practical applications. Computer simulation results show that the proposed max-min power allocation scheme is more robust against channel estimation errors and achieves better *worst bit-error-rate* performance for the two users, as compared with the conventional fixed power allocation approach and the related max-min method derived according to perfect channel state information.

Index Terms—Capacity, imperfect channel estimation, non-orthogonal multiple access (NOMA), power allocation, signal-to-interference-plus-noise ratio (SINR).

I. INTRODUCTION

Power-domain non-orthogonal multiple access, simply abbreviated as NOMA, has emerged as one of the promising techniques for design of future wireless communication systems [1]–[4] due to its significant capacity gain over orthogonal multiple access (OMA). The main concept of NOMA is that the same frequency band can be shared by multiple users for data transmission at the same time slot through multiplexing all users' signals in the power domain. From an information-theoretical point of view, NOMA can achieve the capacity region of a downlink broadcast channel [5], with about 30% improvement in the spectral efficiency and system capacity over OMA [1]. Specifically, a NOMA system of multiple users needs to allocate more power to one user with a worse channel condition in order that successive interference cancellation (SIC) can be successfully performed for the other users with better channel conditions to decode their own messages [6].

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As a consequence, it is crucial for power allocation among all users in a NOMA system to ensure satisfactory performance. In this paper, the focus is on power allocation techniques for downlink NOMA transmission.

There have been a number of power allocation methods proposed for single-carrier downlink NOMA systems under the assumption that perfect channel state information (CSI) is available. In [7], a closed-form power allocation solution was derived for a NOMA-based multiuser beam-forming (BF) system with multiple clusters consisting of two users each, where the sum capacity of a cluster is maximized under a constraint that the user with a worse channel condition at least has capacity equal to that of a conventional multiuser BF system. In [8], the authors considered a two-user multiple-input multiple-output (MIMO) NOMA scenario, and proposed two iterative power allocation algorithms to maximize the sum capacity of the two users under the minimum rate requirement of the user with a worse channel condition. With fairness considerations among users, the authors in [9] adopted a max-min criterion of maximizing the minimum achievable user rate (i.e., user capacity) and a min-max criterion of minimizing the maximum user outage probability to develop two power allocation methods for a multiuser single-input single-output (SISO) NOMA system. The solution for max-min fairness can be obtained by an iterative procedure, and that for min-max fairness is in semi-closed form. In [10], two low-complexity closed-form power allocation solutions were derived for a two-user NOMA system under both SISO and MIMO scenarios based on maximizing the sum capacity under the minimum rate requirements of both users. These two schemes could be regarded as improved versions of those in [8].

For most existing NOMA power allocation algorithms, perfect CSI is assumed to be known *a priori*. Actually, channel estimation errors would occur due to the inevitable noise and the time-varying nature of wireless channels, and this would cause a significant loss in system performance [11]–[14]. The performance degradation is even worse in NOMA systems, since imperfect CSI would also make SIC not successful. To cater for practical situations, some iterative power allocation methods have been proposed for single-carrier downlink SISO-NOMA systems with imperfect channel estimation [15], [16]. The min-max scheme in [15] was derived subject to minimiz-

ing the maximum outage probability bound, and the max-min algorithms in [16] were based on maximizing the minimum user achievable rate. For the max-min approaches, all users need to send dynamic achievable rates back to the base station for updating the users' power values at each iteration, and this feature would degrade the data transmission efficiency.

In this paper, we propose a new power allocation scheme for two-user downlink NOMA systems with imperfect channel estimation under a single-carrier SISO scenario. With the knowledge of channel estimates and the corresponding error variances, approximated capacity expressions are presented, and an optimization problem is formulated subsequently for power allocation between the two users to maximize the minimum approximated user capacity under a total power constraint. Such a max-min optimization problem is equivalent to maximizing the minimum approximated received signal-to-interference-plus-noise ratio (SINR), and a closed-form power allocation formula can be derived based on SINR balancing between the two users. The derived power allocation method is a closed-form solution to a quadratic equation, where the coefficients can easily be calculated according to the estimated channel information and noise variance. As compared with existing iterative power allocation approaches for NOMA systems with imperfect channel estimation, such as those in [15] and [16], the proposed closed-form solution involves lower computational complexity and is more easily realized for practical applications. It is demonstrated by extensive computer simulation results for different scenarios with imperfect channel estimation that the proposed max-min power allocation scheme is better than the conventional fixed power allocation approach and the related max-min method derived under perfect CSI, in terms of the *worst bit-error-rate (BER) performance* between the two users and its robustness to channel estimation errors.

II. SYSTEM MODEL

Consider a downlink SISO-NOMA system with a base station (BS) and two users (1 and 2) as shown in Fig. 1 [1]. The channel fading coefficients between the BS and the two users are denoted by h_1 and h_2 , where $h_k \sim \mathcal{CN}(0, \sigma_{h_k}^2)$ and $\mathcal{CN}(\mu, \sigma^2)$ represents a complex Gaussian random variable with mean μ and variance σ^2 . For ease of presentation, user 1 is referred to as a stronger user with a larger channel (power) gain, while user 2 is referred to as a weak user with a smaller channel gain, i.e., $|h_1|^2 > |h_2|^2$. Denote the random information signals of users 1 and 2 by s_1 and s_2 , respectively, with normalized power $E[|s_1|^2] = E[|s_2|^2] = 1$, where $E[\cdot]$ stands for the statistical expectation. The BS superposes the two-users' information signals appropriately, s_1 with power P_1 and s_2 with power P_2 , to form $x = \sqrt{P_1}s_1 + \sqrt{P_2}s_2$ for NOMA transmission to the two-users' terminals. With the above arrangements, the received signals y_1 and y_2 for users 1 and 2, respectively, can be expressed as follows:

$$y_1 = h_1x + n_1 = \sqrt{P_1}h_1s_1 + \sqrt{P_2}h_1s_2 + n_1 \quad (1)$$

$$y_2 = h_2x + n_2 = \sqrt{P_1}h_2s_1 + \sqrt{P_2}h_2s_2 + n_2 \quad (2)$$

where $n_k \sim \mathcal{CN}(0, \sigma_{n_k}^2)$, $k \in \{1, 2\}$, is an additive white Gaussian noise at the k th-user's terminal. It is assumed that the information signals (s_1, s_2) and the noise terms (n_1, n_2) are assumed to be statistically independent. Also, without loss of generality, noise variances are assumed to be equal, i.e., $\sigma_{n_1}^2 = \sigma_{n_2}^2 = N_0$.

Fig. 1. A two-user downlink SISO-NOMA system [1].

According to the NOMA principle, the transmit power for the strong user's signal must be smaller than that for the weak user's signal, i.e., $P_1 < P_2$. This implies that the weak user can decode its own signal directly by treating the small interference caused by the strong user's signal as noise. On the other hand, the strong user needs to first detect the weak user's signal and then to remove the weak user's signal through an SIC process before decoding its own signal. When perfect CSI is available and the SIC process is successful with no error propagation, exact SINR and capacity formulations can easily be derived at each user's terminal. However, under imperfect channel estimation, additional interference/error terms will be incurred to the signal detection process, and the corresponding exact SINR and capacity formulations are difficult to be found. In the following, approximated SINR and capacity expressions are proposed to develop a power allocation scheme for NOMA systems with imperfect channel estimation.

Let $\hat{h}_k$, $k \in \{1, 2\}$, be a channel estimate of the true channel h_k with the associated channel estimation error modelled as $e_k \sim \mathcal{CN}(0, \sigma_{e_k}^2)$ [12], [13], i.e.,

$$h_k = \hat{h}_k + e_k \quad (3)$$

where $\sigma_{e_k}^2$ can be interpreted as the mean-squared error (MSE) of channel estimation for user k . The MSEs are dependent on the channel estimation schemes and channel variations [12], [17], and they are assumed to be known *a priori* in this paper. Under the above channel uncertainties, the received signals for users 1 and 2 can be rewritten as follows:

$$y_1 = \sqrt{P_1}(\hat{h}_1 + e_1)s_1 + \sqrt{P_2}(\hat{h}_1 + e_1)s_2 + n_1 \quad (4)$$

$$y_2 = \sqrt{P_1}(\hat{h}_2 + e_2)s_1 + \sqrt{P_2}(\hat{h}_2 + e_2)s_2 + n_2. \quad (5)$$

Further assume that the channel estimation errors are statistically independent of the information signals and the noise terms. Then, with the channel estimate $\hat{h}_1$ for the SIC process,

the interference term $\sqrt{P_2}e_1s_2$ in (4) cannot be removed, and we can approximate the received SINR at the strong user's terminal as

$$\text{SINR}_{1,\text{SISO}}^{\text{IP}} \approx \frac{E\{|\sqrt{P_1}(\hat{h}_1 + e_1)s_1|^2\}}{E\{|\sqrt{P_2}e_1s_2 + n_1|^2\}} = \frac{P_1(|\hat{h}_1|^2 + \sigma_{e_1}^2)}{P_2\sigma_{e_1}^2 + N_0}. \quad (6)$$

In this approximation, the known MSE $\sigma_{e_1}^2$ is considered as part of the signal power, rather than as part of the interference-plus-noise power. Similarly, from (5), the received SINR at the weak user's terminal can be approximated by

$$\begin{aligned} \text{SINR}_{2,\text{SISO}}^{\text{IP}} &\approx \frac{E\{|\sqrt{P_2}(\hat{h}_2 + e_2)s_2|^2\}}{E\{|\sqrt{P_1}(\hat{h}_2 + e_2)s_1 + n_2|^2\}} \\ &= \frac{P_2(|\hat{h}_2|^2 + \sigma_{e_2}^2)}{P_1(|\hat{h}_2|^2 + \sigma_{e_2}^2) + N_0}. \end{aligned} \quad (7)$$

Accordingly, the SISO capacity for the strong user under imperfect channel estimation can be approximated as

$$C_{1,\text{SISO}}^{\text{IP}} \approx \log_2(1 + \text{SINR}_{1,\text{SISO}}^{\text{IP}}) = \log_2\left(1 + \frac{P_1(|\hat{h}_1|^2 + \sigma_{e_1}^2)}{P_2\sigma_{e_1}^2 + N_0}\right) \quad (8)$$

and the corresponding SISO capacity for the weak user can be approximated as

$$\begin{aligned} C_{2,\text{SISO}}^{\text{IP}} &\approx \log_2(1 + \text{SINR}_{2,\text{SISO}}^{\text{IP}}) \\ &= \log_2\left(1 + \frac{P_2(|\hat{h}_2|^2 + \sigma_{e_2}^2)}{P_1(|\hat{h}_2|^2 + \sigma_{e_2}^2) + N_0}\right). \end{aligned} \quad (9)$$

III. MAX-MIN POWER ALLOCATION FOR A TWO-USER DOWNLINK NOMA SYSTEM

A. Power Allocation Problem Formulation

To maximize the minimum approximated user capacity of the two-user downlink SISO NOMA system under imperfect channel estimation in Fig. 1, we can formulate an optimization problem under a total transmit power P_T as follows:

$$\max_{\{P_1, P_2\}} \min(C_{1,\text{SISO}}^{\text{IP}}, C_{2,\text{SISO}}^{\text{IP}}) \quad (10a)$$

$$\text{subject to } P_1 + P_2 = P_T \quad (10b)$$

$$P_1 > 0, P_2 > 0, P_2 > P_1 \quad (10c)$$

where the strong user capacity $C_{1,\text{SISO}}^{\text{IP}}$ and the weak user capacity $C_{2,\text{SISO}}^{\text{IP}}$ are approximately given by (8) and (9), respectively, constraint (10b) represents the total transmit power constraint, and constraint (10) reflects the NOMA principle. Define $\alpha_{\text{SISO}}^{\text{IP}}$ to be the power allocation factor between the two users with $P_1 = \alpha_{\text{SISO}}^{\text{IP}}P_T$ and $P_2 = (1 - \alpha_{\text{SISO}}^{\text{IP}})P_T$. Then, with the fact that maximizing the minimum approximated user capacity is equivalent to maximizing the minimum approximated received SINR, the max-min optimization problem can be reformulated by

$$\max_{\alpha_{\text{SISO}}^{\text{IP}}} \min(\text{SINR}_{1,\text{SISO}}^{\text{IP}}(\alpha_{\text{SISO}}^{\text{IP}}), \text{SINR}_{2,\text{SISO}}^{\text{IP}}(\alpha_{\text{SISO}}^{\text{IP}})) \quad (11a)$$

$$\text{subject to } P_1 + P_2 = P_T \quad (11b)$$

$$0 < \alpha_{\text{SISO}}^{\text{IP}} < 1/2 \quad (11c)$$

where $\text{SINR}_{1,\text{SISO}}^{\text{IP}}(\alpha_{\text{SISO}}^{\text{IP}})$ and $\text{SINR}_{2,\text{SISO}}^{\text{IP}}(\alpha_{\text{SISO}}^{\text{IP}})$ are obtained from (6) and (7), respectively, by replacing P_1 with $\alpha_{\text{SISO}}^{\text{IP}}P_T$ and replacing P_2 with $(1 - \alpha_{\text{SISO}}^{\text{IP}})P_T$.

B. A Power Allocation Solution Based on SINR Balancing

As described by the works of [18] and [19], the optimal solution to the max-min problem of (11a)-(11c) occurs when SINR balancing is used, i.e., $\text{SINR}_{1,\text{SISO}}^{\text{IP}}(\alpha_{\text{SISO}}^{\text{IP}}) = \text{SINR}_{2,\text{SISO}}^{\text{IP}}(\alpha_{\text{SISO}}^{\text{IP}})$ in (6) and (7). Thus, a power allocation factor $\alpha_{\text{SISO}}^{\text{IP}}$ for maximizing the minimum approximated user capacity of the two-user downlink SISO NOMA system under imperfect channel estimation (referred to as the SISO-MaxMin-IP scheme) can be derived by solving a quadratic equation of $a(\alpha_{\text{SISO}}^{\text{IP}})^2 + b(\alpha_{\text{SISO}}^{\text{IP}}) + c = 0$ and the solution is

$$\alpha_{\text{SISO}}^{\text{IP}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \quad (12a)$$

$$a = P_T|\hat{h}_1|^2(|\hat{h}_2|^2 + \sigma_{e_2}^2) \quad (12b)$$

$$b = N_0(|\hat{h}_1|^2 + |\hat{h}_2|^2 + \sigma_{e_1}^2 + \sigma_{e_2}^2) + 2P_T\sigma_{e_1}^2(|\hat{h}_2|^2 + \sigma_{e_2}^2) \quad (12c)$$

$$c = -(P_T\sigma_{e_1}^2 + N_0)(|\hat{h}_2|^2 + \sigma_{e_2}^2). \quad (12d)$$

Since the capacity expressions under imperfect channel estimation are not exact, $\alpha_{\text{SISO}}^{\text{IP}}$ derived above can only be regarded as a suboptimal power allocation factor. Also, $\alpha_{\text{SISO}}^{\text{IP}}$ must satisfy constraint (11c) so that the strong user can detect the weak user's signal and perform SIC successfully. Since $a > 0$, $b > 0$, and $c < 0$ from (12b)-(12d), the term $\sqrt{b^2 - 4ac}$ is greater than b and $\alpha_{\text{SISO}}^{\text{IP}}$ is greater than 0. To ensure that $\alpha_{\text{SISO}}^{\text{IP}}$ is smaller than 1/2, we need to show $a > -b + \sqrt{b^2 - 4ac}$, i.e., to show $a + 2b + 4c > 0$. According to (12b)-(12d), we can have the following derivations:

$$\begin{aligned} &a + 2b + 4c \\ &= P_T|\hat{h}_1|^2(|\hat{h}_2|^2 + \sigma_{e_2}^2) + 2\{N_0(|\hat{h}_1|^2 + |\hat{h}_2|^2 + \sigma_{e_1}^2 + \sigma_{e_2}^2) \\ &\quad + 2P_T\sigma_{e_1}^2(|\hat{h}_2|^2 + \sigma_{e_2}^2)\} - 4(P_T\sigma_{e_1}^2 + N_0)(|\hat{h}_2|^2 + \sigma_{e_2}^2) \\ &= P_T|\hat{h}_1|^2(|\hat{h}_2|^2 + \sigma_{e_2}^2) - 4N_0(|\hat{h}_2|^2 + \sigma_{e_2}^2) + 2N_0(|\hat{h}_1|^2 \\ &\quad + |\hat{h}_2|^2 + \sigma_{e_1}^2 + \sigma_{e_2}^2) \\ &= P_T|\hat{h}_1|^2(|\hat{h}_2|^2) + 2N_0(|\hat{h}_1|^2 + \sigma_{e_1}^2 - |\hat{h}_2|^2 - \sigma_{e_2}^2). \end{aligned} \quad (13)$$

With the fact that the strong user's channel gain $|h_1|^2$ is larger than the weak user's channel gain $|h_2|^2$, it is reasonable to assume that $\sigma_{e_1}^2 > \sigma_{e_2}^2$ and $|\hat{h}_1|^2 + \sigma_{e_1}^2 > |\hat{h}_2|^2 + \sigma_{e_2}^2$ under appropriate channel estimation. Accordingly, $a + 2b + 4c > 0$ holds and $\alpha_{\text{SISO}}^{\text{IP}}$ satisfies the constraint of $0 < \alpha_{\text{SISO}}^{\text{IP}} < 1/2$.

Note that the optimal power allocation factor $\alpha_{\text{SISO}}^{\text{P}}$ for maximizing the minimum user capacity of the two-user downlink SISO-NOMA system under perfect CSI (referred to as the SISO-MaxMin-P scheme) can also be derived by SINR balancing in a similar way. Moreover, SISO-MaxMin-IP is identical to SISO-MaxMin-P when there are no channel estimation errors. Under imperfect channel estimation, the SISO-MaxMin-IP scheme applies channel estimates and the associated MSEs to calculate the power allocation factor. In contrast, the SISO-MaxMin-P method does not consider

the MSEs and just uses channel estimates as true channel gains to determine the power allocation factor. Since the proposed power allocation method is a closed-form solution to a quadratic equation, it involves low computational complexity and can easily be realized in practical applications.

IV. SIMULATION RESULTS

A. Simulation Arrangements

In this section, computer simulation results are provided to evaluate the performance of the proposed SISO-MaxMin-IP power allocation method under imperfect channel estimation. All the simulations were conducted for 10^5 independent channel realizations based on the common path-loss model [20], where the strong user is closer to the BS and the weak user is farther from the BS. The variance of the strong user's channel gain was set by $\sigma_{h_1}^2 = 1$, the variance of the weak user's channel gain was set by $\sigma_{h_2}^2 = 0.1$ (10 dB less than $\sigma_{h_1}^2$), and the noise variance at each user's terminal was set by $N_0 = 1$. The total transmit power P_T for the BS is equal to $10^{SNR/10}$ with $SNR = \log_{10}(P_T/N_0)$ as the signal-to-noise ratio (dB). The performance metrics considered for simulations include the capacity and BER, and the BER performance was evaluated by using quadrature phase shift keying (QPSK) modulation at the transmitter (BS) and linear minimum mean-squared error (MMSE) detection [21] at the receivers (users' terminals). Also, to better capture the quality of channel estimation, we defined the normalized channel MSE as $\tilde{\sigma}_{e_k}^2 = \sigma_{e_k}^2 / \sigma_{h_k}^2$, $k \in \{1, 2\}$. For the purpose of comparison, simulations were also performed for SISO-MaxMin-P and the fixed power allocation approach (Fixed PA) with the power allocation factor equal to 0.2 for the strong user and 0.8 for the weak user [1].

B. Performance Evaluations

Fig. 2 shows simulation results of the minimum approximated user capacity for the SISO-MaxMin-IP power allocation scheme versus SNR for some situations with equal normalized channel MSEs for the two users, where $\tilde{\sigma}_{e_1}^2 = \tilde{\sigma}_{e_2}^2$ was set for each case. It can be seen that the minimum approximated user capacity performance under imperfect channel estimation is getting closer to the capacity performance under perfect CSI ($\tilde{\sigma}_{e_1}^2 = \tilde{\sigma}_{e_2}^2 = 0$) when the normalized channel MSEs are getting smaller. This supports that the approximated SISO capacity expressions under imperfect channel estimation given in (8) and (9) are reasonable. Figs. 3 and 4 further present the corresponding average BER performance of the strong user (SU) and weak user (WU) and the *worst BER performance* between the two users for SISO-MaxMin-IP for some situations with equal normalized channel MSEs. It is clear that the SISO-MaxMin-IP method works well and the BER performance is getting better with the decreasing of normalized channel MSEs. Similar results can also be seen for other situations with different or equal normalized channel MSEs for the two users, as shown by the *worst BER performance* in Fig. 5.

Figs. 6-9 give BER simulation results of SISO-MaxMin-IP, SISO-MaxMin-P (using $|\hat{h}_k|^2$ as $|h_k|^2$ under imperfect channel

estimation), and Fixed PA for the two users with normalized channel MSEs equal to 0.01, i.e., $\tilde{\sigma}_{e_1}^2 = \tilde{\sigma}_{e_2}^2 = 0.01$. It can be observed that SISO-MaxMin-IP achieves closer BER performance between SU and WU as well as better *worst BER performance* than the other two methods. Similar results can also be obtained when the normalized channel MSEs are smaller or larger. All these results demonstrate that SISO-MaxMin-IP has better BER performance and is more robust against channel estimation errors than SISO-MaxMin-P and Fixed PA. Note that SISO-MaxMin-P is identical to SISO-MaxMin-IP under $\tilde{\sigma}_{e_1}^2 = \tilde{\sigma}_{e_2}^2 = 0$, but its BER performance would be degraded significantly under imperfect channel estimation. This result further supports that the effectiveness and usefulness of the proposed SISO-MaxMin-IP scheme which uses channel estimates and the corresponding channel MSEs properly for power allocation.

Fig. 2. Minimum approximated user capacity performance of SISO-MaxMin-IP for some situations with equal normalized channel MSEs for the two users.

V. CONCLUSION

Most existing power allocation algorithms for downlink NOMA systems require the use of perfect CSI, and their performance would be degraded significantly in real environments with imperfect channel estimation. In this paper, a new power allocation scheme has been developed for a downlink SISO-NOMA system with a base station and two users in the presence of channel estimation errors. Given channel estimates and the corresponding mean-squared errors, approximated user capacity expressions have been proposed, and then a closed-form power allocation solution has been derived accordingly by maximizing the minimum approximated user capacity under a total power constraint, i.e., by SINR balancing between the two users. The proposed power allocation method is a closed-form solution to a quadratic equation and involves low implementation complexity. Computer simulations have been conducted for different scenarios with imperfect channel

Fig. 3. Average BER performance of SISO-MaxMin-IP for some situations with equal normalized channel MSEs for the two users.

Fig. 5. Worst BER performance of SISO-MaxMin-IP for some situations with equal or different normalized channel MSEs for the two users.

Fig. 4. Worst BER performance of SISO-MaxMin-IP for some situations with equal normalized channel MSEs for the two users.

Fig. 6. BER performance of SISO-MaxMin-IP for the two users with normalized channel MSEs equal to 0.01.

estimation. The simulation results have demonstrated that the proposed max-min power allocation scheme derived under imperfect channel estimation outperforms the conventional fixed power allocation approach and the related max-min method derived under perfect CSI in terms of the *worst BER performance* between the two users and its robustness to channel estimation errors. Both low-complexity and good-performance features make the proposed power allocation method attractive for use in practical applications.

Although the proposed power allocation scheme for downlink NOMA systems with imperfect channel estimation is limited to the single-carrier two-user case, it can be extended to the general multicarrier multiuser case by properly combining

NOMA and orthogonal frequency division multiple access (OFDMA) together, just like the multicarrier NOMA system described in [19]. In such a multiuser OFDMA-based NOMA system, every two users can form a group to share some subcarriers for NOMA transmission, where appropriate user pairing, subcarrier allocation, and power allocation algorithms need to be developed for further performance enhancement.

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Fig. 7. BER performance of SISO-MaxMin-P for the two users with normalized channel MSEs equal to 0.01.

Fig. 8. BER performance of Fixed PA for the two users with normalized channel MSEs equal to 0.01.

Fig. 9. Comparison of worst BER performance for SISO-MaxMin-IP, SISO-MaxMin-P, and Fixed PA under normalized channel MSEs equal to 0.01 for the two users.

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