Improving Physical Layer Security of NOMA Networks by Using Opportunistic Scheduling

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***Abstract*—In this paper, we study how to improve physical layer security capability of multiple near users and multiple far users non-orthogonal multiple access (NOMA) networks. To this end, we propose an opportunistic user scheduling scheme, named the best-secure-near-user best-secure-far-user (BSNBSF) scheme. The BSNBSF aims to select the best near-far user pair, whose data transmission is the most robust against the interception of an eavesdropper. In order to facilitate the performance analysis of the proposed user scheduling scheme in terms of secrecy outage probability (SOP), we derive an exact closed-form expression and a tight approximate closed-form expression for the SOP of the selected near and far users, respectively. Numerical results show that the BSNBSF scheme significantly improves the secrecy outage performance NOMA networks compared to that of the random near user and random far user selection scheme. Additionally, discussions on the complicate convex characteristic of the total SOP with respect to the power allocation coefficients and the impact the number of near and/or far users are provided.**

I. Introduction

Non-orthogonal multiple access (NOMA) has been emerging as a rising solution to improve the spectral efficiency for the future wireless communication system [1]–[4]. From the principle of NOMA, which allocates the different power coefficient to each users depending on the channel state information (CSI) [5], [6]. For example, in the downlink two user NOMA system consists of base station, near user (that has high CSI), and far user (that has low CSI). The base station transmits messages to both users using the superposition coding and more transmission power allocated to the far user, where the power allocation of the far user is higher than that of the near user. Under the NOMA scheme, the near user firstly decode and subtract the far user message by using the successive interference cancellation (SIC) technique [5]. The signal to the far user can be decoded without interference elimination from the signal to the near user. It is noteworthy that the two-user NOMA scheme seems the most realizable and preferable among NOMA schemes proposed in industrial [1], [2] and in the literature [3], [4].

NOMA system is useful to communicate with multiple users since the principle of NOMA technique superposes the multiple user information into one signal. On the contrary, if an eavesdropper is able to overhear the message, it has the problem that the whole user information is opened to the eavesdropper. Thus, in NOMA system, the security issue is more important rather than the conventional OMA system. One possible solution to combat against eavesdropping attacks to NOMA transmissions is to use physical layer security technique. Physical layer security (PLS) prevents information intercept from an eavesdropper using the nature of wireless medium in terms of the information theory as in [7].

The physical layer security (PLS) technique has been demonstrated as a sustainable mean to cope with security issues in NOMA networks. Indeed, the authors of [8] proposed the transmit antenna selection (TAS) scheme to improve the security performance for the down link NOMA system consisting of multiple antenna base station, two-user, and one eavesdropper. The authors of [9] studied the physical layer security for NOMA in large-scale networks. This paper consisted of the single-antenna base station, the receivers were uniformly distributed within the disc, and the eavesdroppers were distributed in an infinite two dimension via a homogeneous Poisson point process (PPP). The authors derived the new exact and asymptotic expressions for the security outage probability. This paper was extended into the case of the multi-antenna base station from the case of the single antenna base station in [10].

In this paper, we propose the new user selection scheme for multi-near and multi-far user NOMA systems using opportunistic scheduling. It is noteworthy that in uplink/downlink scenarios of the wireless communication, where the opportunistic scheduling is that a single source transmits to the selected user to improve the transmission performance [11], [12] since the channel condition is varying the nature of the wireless channels. The main contributions and features are summarized as:

- We propose an opportunistic user scheduling scheme, named the best-secure-near-user best-secure-far-user (BSNBSF) scheme. The BSNBSF aims to select the best near-far user pair, whose data transmission is the most robust against the interception of an eavesdropper. Specifically, in order to select the best user pair in a certain time slot, we take into account the channel quality of both main and eavesdropper channels.
- We derive an exact closed-form expression and a tight approximate closed-form expression for the SOP of the selected near and far users, respectively, which have not been reported in the literature. The developed analysis is then validated by Monte-Carlo simulation.
- Through the numerical results, we show that the BSNBSF

scheme significantly improves the secrecy outage performance NOMA networks compared to that of the random near user and random far user selection scheme. Additionally, the total SOP of the considered network poses a complicate convex characteristic with respect to the power allocation coefficients. Moreover, the robustness of the proposed scheduling scheme can be better by increasing number of participant near and/or far users.

Notations: $X \sim \mathcal{CN}(0, \sigma^2)$ denotes a circularly symmetric complex Gaussian random variable X with zero mean and variance σ^2; $\Pr(\cdot)$ is the probability; $f_X(\cdot)$ and $F_X(\cdot)$ represent the probability density function (PDF) and cumulative distribution function (CDF) of the random variable X, respectively. $\mathbb{E}[\cdot]$ denotes the statistical expectation operator.

II. System Model

Let us consider a downlink two-user NOMA system that includes a base station (S), a set of K near users, $\mathcal{N} = \{\mathsf{N}_i | i = 1, 2, ..., K\}$, and a set of M far users, $\mathcal{F} = \{\mathsf{F}_j | j = 1, 2, ..., M\}$, and an eavesdropper ($\mathsf{E}$), as shown in Fig. 1. More specifically, the near users can perfectly subtract the message. The near users can perfectly use the successive interference cancellation (SIC) technique to subtract the far x_{F_j} [8]. Both the legitimate and illegitimate receivers are equipped with a single antenna and operate in half-duplex mode. All wireless links are assumed to undergo independent and identically distributed (i.i.d.) Rayleigh block flat fading. Let h_{XY} and $|h_{\mathsf{XY}}|^2$ denote the channel coefficient and the corresponding channel gain, respectively, of $\mathsf{X} \to \mathsf{Y}$ channel; let ω_{Y} denote the additive white Gaussian noise (AWGN) at node Y, where $\mathsf{X} \in \{\mathsf{S}\}, \mathsf{Y} \in \mathcal{N} \cup \mathcal{F} \cup \{\mathsf{E}\}$. The average channel gain can be written as $\lambda_{\mathsf{XY}} = (d_{\mathsf{XY}}/d_0)^{-\epsilon}\mathcal{L}$, where $\mathcal{L}$ is the reference signal power attenuation, d_{XY} denotes the distance between X and Y, d_0 presents the reference distance, and ϵ is the path-loss exponent [4]. And the channel noise is followed $\omega_{\mathsf{Y}} \sim \mathcal{CN}(0, \sigma^2_{\mathsf{Y}})$. We also assume that the source perfectly knows the channel state information (CSI) of all legitimate users and eavesdropper, as in [11], [12].

A. Communication Process

In this subsection, we present the communication process in two-user NOMA system in detail. Assuming that N_i and F_j are selected to receive its data from the S in a certain time slot. From the principle of NOMA, the message x_{N_i} and x_{F_j} that will be allocated to θ_{N_i} and θ_{F_j}, respectively, are superposed as $\sqrt{\theta_{\mathsf{N}_i}}x_{\mathsf{N}_i} + \sqrt{\theta_{\mathsf{F}_j}}x_{\mathsf{F}_j}$ and then broadcasted by S, where θ_{N_i} and θ_{F_j} denote the power allocation coefficient. We suppose that $|h_{\mathsf{SN}_i}|^2 > |h_{\mathsf{SF}_j}|^2$, and set $0 < \theta_{\mathsf{N}_i} < \theta_{\mathsf{F}_j}$ and $\theta_{\mathsf{N}_i} + \theta_{\mathsf{F}_j} = 1$ as in [6].

At the near user N_i, the received signal is given by

$$y_{\mathsf{SN}_i} = \sqrt{P_{\mathsf{S}}\theta_{\mathsf{N}_i}}h_{\mathsf{SN}_i}x_{\mathsf{N}_i} + \sqrt{P_{\mathsf{S}}\theta_{\mathsf{F}_j}}h_{\mathsf{SN}_i}x_{\mathsf{F}_j} + \omega_{\mathsf{N}_i}, \quad (1)$$

where P_{S} denotes the transmit power of the S. Because of the power allocated coefficient condition, the near user need to subtract the component, x_{F_j}, from the y_{SN_i} using the SIC process [13]. The signal-to-interference-plus-noise-ratio (SINR) of the eliminated component, x_{F_j}, is expressed as

$$\gamma^{x_{\mathsf{F}_j}}_{\mathsf{SN}_i} = \frac{P_{\mathsf{S}}\theta_{\mathsf{F}_j}|h_{\mathsf{SN}_i}|^2}{P_{\mathsf{S}}\theta_{\mathsf{N}_i}|h_{\mathsf{SN}_i}|^2 + \sigma^2_{\mathsf{SN}_i}}, \quad (2)$$

after the SIC, the N_i archives its own message, x_{N_i}, from the received signal which signal-to-noise-ratio (SNR) is obtained as

$$\gamma^{x_{\mathsf{N}_i}}_{\mathsf{SN}_i} = \frac{P_{\mathsf{S}}\theta_{\mathsf{N}_i}|h_{\mathsf{SN}_i}|^2}{\sigma^2_{\mathsf{SN}_i}}. \quad (3)$$

At the far user F_j, the received signal is given by

$$y_{\mathsf{SF}_j} = \sqrt{P_{\mathsf{S}}\theta_{\mathsf{F}_j}}h_{\mathsf{SF}_j}x_{\mathsf{F}_j} + \sqrt{P_{\mathsf{S}}\theta_{\mathsf{N}_i}}h_{\mathsf{SF}_j}x_{\mathsf{N}_i} + \omega_{\mathsf{F}_j}. \quad (4)$$

Different from the near user, the F_j directly decodes the SINR from the received signal because of the power allocated coefficient condition. The received SINR at F_j to decode x_{F_j} is given by

$$\gamma^{x_{\mathsf{F}_j}}_{\mathsf{SF}_j} = \frac{P_{\mathsf{S}}\theta_{\mathsf{F}_j}|h_{\mathsf{SF}_j}|^2}{P_{\mathsf{S}}\theta_{\mathsf{N}_i}|h_{\mathsf{SF}_j}|^2 + \sigma^2_{\mathsf{SF}_j}}. \quad (5)$$

Meanwhile, the eavesdropper can intercept the signal due to the broadcast nature of wireless medium. Thus, the received signal at E can be written as

$$y_{\mathsf{SE}} = \sqrt{P_{\mathsf{S}}\theta_{\mathsf{N}_i}}h_{\mathsf{SE}}x_{\mathsf{F}_j} + \sqrt{P_{\mathsf{S}}\theta_{\mathsf{F}_j}}h_{\mathsf{SE}}x_{\mathsf{N}_i} + \omega_{\mathsf{E}}. \quad (6)$$

Different from the legitimate user, we assume that the E has enough ability to distinguish each message from the received signal. Thus, the SINRs of the received signal are given by

$$\gamma^{x_{\mathsf{F}_j}}_{\mathsf{SE}} = \frac{P_{\mathsf{S}}\theta_{\mathsf{F}_j}|h_{\mathsf{SE}}|^2}{P_{\mathsf{S}}\theta_{\mathsf{N}_i}|h_{\mathsf{SE}}|^2 + \sigma^2_{\mathsf{SE}}}, \quad (7)$$

and

$$\gamma^{x_{\mathsf{N}_i}}_{\mathsf{SE}} = \frac{P_{\mathsf{S}}\theta_{\mathsf{N}_i}|h_{\mathsf{SE}}|^2}{\sigma^2_{\mathsf{SE}}}, \quad (8)$$

respectively.

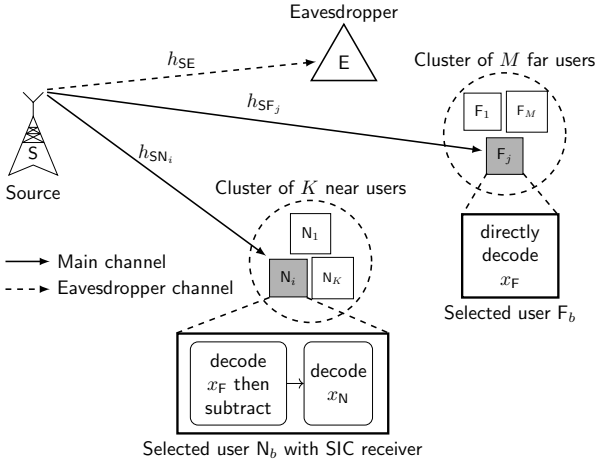

Fig. 1. System model consisting of a Base station, two multiple receiver and one eavesdropper, all equipped with a single antenna.

In physical layer security, the secrecy capacity means that the difference between main channel capacity and eavesdropper channel capacity. Thus, in two-user NOMA system, the secrecy capacity of x_{N_i} and x_{F_j} is given by [8], [14]

$$C_{s,\mathsf{N}_i} = \left[\log_2(1+\gamma_{\mathsf{SN}_i}^{x_{\mathsf{N}_i}}) - \log_2(1+\gamma_{\mathsf{SE}}^{x_{\mathsf{N}_i}})\right]^+, \quad (9)$$

$$C_{s,\mathsf{F}_j} = \left[\log_2(1+\gamma_{\mathsf{SF}_j}^{x_{\mathsf{F}_j}}) - \log_2(1+\gamma_{\mathsf{SE}}^{x_{\mathsf{F}_j}})\right]^+, \quad (10)$$

respectively, where $[x]^+ = \max\{x, 0\}$.

B. The Proposed Best-Secure-Near-User Best-Secure-Far-User (BSNBSF) Scheme

The proposed user selection process is conducted through the channel state information (CSI) estimation/calculation system. Thus, this process is carried out before the data communication process as in [11], [12]. In this paper, we propose the BSNBSF user selection scheme to maximize the secrecy capacity at N_i and F_j, respectively. The proposed scheme can be mathematically expressed as

$$\mathsf{N}_b = \arg\max_{i\in\mathcal{N}} \left\{ \log_2 \left(\frac{1+\gamma_{\mathsf{SN}_i}^{x_{\mathsf{N}_i}}}{1+\gamma_{\mathsf{SE}}^{x_{\mathsf{N}_i}}} \right) \right\}, \quad (11)$$

and

$$\mathsf{F}_b = \arg\max_{j\in\mathcal{F}} \left\{ \log_2 \left(\frac{1+\gamma_{\mathsf{SF}_j}^{x_{\mathsf{F}_j}}}{1+\gamma_{\mathsf{SE}}^{x_{\mathsf{F}_j}}} \right) \right\}. \quad (12)$$

(11) and (12) mean that the selected users are the best secrecy capacity of a certain time slot.

III. Secrecy Outage Performance Analysis

In this section, the performance investigation of the proposed user selection scheme in terms of secrecy outage probability (SOP) is presented. Because the wireless channels undergo i.i.d. Rayleigh fading, for the sake of notational convenience, we assume that $\lambda_{\mathsf{SN}_1} = \lambda_{\mathsf{SN}_2} = ... \lambda_{\mathsf{SN}_i} = \lambda_{\mathsf{SN}}$, $\lambda_{\mathsf{SF}_1} = \lambda_{\mathsf{SF}_2} = ... \lambda_{\mathsf{SF}_j} = \lambda_{\mathsf{SF}}$.

Note that the fixed mechanism has been widely used since it does not increase the complexity of the performance analysis while it still reflects the principle as well as the performance efficiency of NOMA. [3]. Thus, without loss of generality, we further assume that $\theta_{\mathsf{N}_1} = \theta_{\mathsf{N}_2} = ... = \theta_{\mathsf{N}_i} = \theta_{\mathsf{N}}$ and $\theta_{\mathsf{F}_1} = \theta_{\mathsf{F}_2} = ... = \theta_{\mathsf{N}_j} = \theta_{\mathsf{F}}$.

We also assume the all nodes have the same noise variance, let $\gamma = P_{\mathsf{S}}/\sigma^2$ present the transmit SNR as in [8], [11]. The SOP of a user can be defined as the probability that the instantaneous secrecy capacity of the user falls below a predefined target data rate [10]. Thus, the SOPs at N_b and F_b are obtained as

$$P_{\mathsf{SOP},\mathsf{N}_b} = \Pr\left(C_{s,\mathsf{N}_b} < R_{\mathrm{th},\mathsf{N}_b}\right), \quad (13)$$

and

$$P_{\mathsf{SOP},\mathsf{F}_b} = \Pr\left(C_{s,\mathsf{F}_b} < R_{\mathrm{th},\mathsf{F}_b}\right), \quad (14)$$

where R_{th,N_b} and R_{th,F_b} denote the target data rate at N_b and F_b, respectively.

At the selected near user, the SOP of N_b can be expressed as

$$P_{\mathsf{SOP},\mathsf{N}_b} = \Pr\left(\log_2 \left(\frac{1+\gamma\theta_{\mathsf{N}}|h_{\mathsf{SN}_b}|^2}{1+\gamma\theta_{\mathsf{N}}|h_{\mathsf{SE}}|^2} \right) < R_{\mathrm{th},\mathsf{N}_b} \right). \quad (15)$$

Since all of the wireless channels are assumed to be independent, (15) can be re-written as

$$P_{\mathsf{SOP},\mathsf{N}_b} = \Pr\left(\max_{i\in\mathcal{N}} \left\{ \frac{1+\gamma\theta_{\mathsf{N}}|h_{\mathsf{SN}_i}|^2}{1+\gamma\theta_{\mathsf{N}}|h_{\mathsf{SE}}|^2} \right\} < \gamma_{\mathrm{th},\mathsf{N}_b} \right), \quad (16)$$

where $\gamma_{\mathrm{th},\mathsf{N}_b} \triangleq 2^{R_{\mathrm{th},\mathsf{N}_b}}$. As we can observe that the events of the probability in (16) are not mutually exclusive because they include the same components $|h_{\mathsf{SE}}|^2$, therefore conditioning on $|h_{\mathsf{SE}}|^2 = z$, the $P_{\mathsf{SOP},\mathsf{N}_b}$ can be further expressed as:

$$\begin{aligned} &P_{\mathsf{SOP},\mathsf{N}_b} \\ &= \int_0^\infty \Pr\left(\bigcap_{i=1}^{K} \left(\frac{1+\gamma\theta_{\mathsf{N}}|h_{\mathsf{SN}_i}|^2}{1+\gamma\theta_{\mathsf{N}}z} < \gamma_{\mathrm{th},\mathsf{N}_b} \right) \right) f_Z(z)dz \\ &= \int_0^\infty \prod_{i=1}^{K} \underbrace{\Pr\left(|h_{\mathsf{SN}_i}|^2 < \frac{\gamma_{\mathrm{th},\mathsf{N}_b}-1}{\gamma\theta_{\mathsf{N}}} + \gamma_{\mathrm{th},\mathsf{N}_b}z \right)}_{\Psi} f_Z(z)dz. \end{aligned} \quad (17)$$

For the sake of notational convenience, let $X_i \triangleq |h_{\mathsf{SN}_i}|^2$, Ψ in (17) can be re-written as:

$$\Psi = \int_0^{\frac{\gamma_{\mathrm{th},\mathsf{N}_b}-1}{\gamma\theta_{\mathsf{N}}} + \gamma_{\mathrm{th},\mathsf{N}_b}z} f_{X_i}(x)dx. \quad (18)$$

After some algebra manipulations, Ψ can be obtained as:

$$\Psi = 1 - \exp\left(-\frac{1}{\lambda_{\mathsf{SN}}} \left(\frac{\gamma_{\mathrm{th},\mathsf{N}_b}-1}{\gamma\theta_{\mathsf{N}}} + \gamma_{\mathrm{th},\mathsf{N}_b}z \right) \right). \quad (19)$$

Plugging (19) into (17), and making use the fact that [15, Eq. (1.111)]

$$(a+b)^N = \sum_{k=0}^{N} \binom{N}{k} a^{N-k}b^k,$$

$P_{\mathsf{SOP},\mathsf{N}_b}$ in (17) can be further expressed as :

$$\begin{aligned} P_{\mathsf{SOP},\mathsf{N}_b} = &\sum_{n=0}^{K} \binom{K}{n} (-1)^n \frac{1}{\lambda_{\mathsf{SE}}} \exp\left(-\frac{n(\gamma_{\mathrm{th},\mathsf{N}_b}-1)}{\lambda_{\mathsf{SN}}\gamma\theta_{\mathsf{N}}} \right) \\ &\times \int_0^\infty \exp\left(-\left(\frac{n\gamma_{\mathrm{th},\mathsf{N}_b}}{\lambda_{\mathsf{SN}}} + \frac{1}{\lambda_{\mathsf{SE}}} \right) z \right) dz. \end{aligned} \quad (20)$$

After some algebra manipulations and making use the fact that $\int_0^\infty \exp(-\frac{1}{a}x)dx = a$, the $P_{\mathsf{SOP},\mathsf{N}_b}$ can be further obtained as

$$\begin{aligned} &P_{\mathsf{SOP},\mathsf{N}_b} \\ &= \sum_{n=0}^{K} \binom{K}{n} (-1)^n \frac{\lambda_{\mathsf{SN}}}{n\gamma_{\mathrm{th},\mathsf{N}_b}\lambda_{\mathsf{SE}} + \lambda_{\mathsf{SN}}} \exp\left(-\frac{n(\gamma_{\mathrm{th},\mathsf{N}_b}-1)}{\lambda_{\mathsf{SN}}\gamma\theta_{\mathsf{N}}} \right). \end{aligned} \quad (21)$$

At the selected far user, the SOP of F_b can be expressed as

$$P_{\mathsf{SOP},\mathsf{F}_b} = \Pr\left(\log_2 \left(\frac{1+\frac{\gamma\theta_{\mathsf{F}}|h_{\mathsf{SF}_b}|^2}{\gamma\theta_{\mathsf{N}}|h_{\mathsf{SF}_b}|^2+1}}{1+\frac{\gamma\theta_{\mathsf{F}}|h_{\mathsf{SE}}|^2}{\gamma\theta_{\mathsf{N}}|h_{\mathsf{SE}}|^2+1}} \right) < R_{\mathrm{th},\mathsf{F}_b} \right). \quad (22)$$

Similar to the case of the selected near user, the events of the probability in (22) are not mutually exclusive because they include the same components $\frac{\gamma\theta_{\mathsf{F}}|h_{\mathsf{SE}}|^2}{\gamma\theta_{\mathsf{N}}|h_{\mathsf{SE}}|^2+1}$. Therefore, conditioning on $\frac{\gamma\theta_{\mathsf{F}}|h_{\mathsf{SE}}|^2}{\gamma\theta_{\mathsf{N}}|h_{\mathsf{SE}}|^2+1} = t$, (22) can be re-written as

$$P_{\mathsf{SOP},\mathsf{F}_b} = \int_0^{\infty}\prod_{j=1}^{M}\underbrace{\Pr\left(\frac{\gamma\theta_{\mathsf{F}}|h_{\mathsf{SF}_j}|^2}{\gamma\theta_{\mathsf{N}}|h_{\mathsf{SF}_j}|^2+1} < \gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}t\right)}_{\Phi} f_T(t)dt. \tag{23}$$

In order to further simplify the integral (23), The following lemma enables us to characterize the SINR at far user and eavesdropper to decode x_{F_j}.

Lemma 1. *Suppose that* $U \triangleq \frac{\gamma\theta_{\mathsf{F}}\rho}{\gamma\theta_{\mathsf{N}}\rho+1}$ $(\rho \in \{|h_{\mathsf{SF}_j}|^2, |h_{\mathsf{SE}}|^2\})$, *the cumulative distribution function (CDF) and probability density function (PDF) can be expressed as:*

$$F_U(u) = \begin{cases} 1-\varphi(\lambda_U, u), & \text{if } 0 \le u < \frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}}, \\ 1, & \text{if } \frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}} \le u, \end{cases} \tag{24}$$

and

$$f_U(u) = \begin{cases} \dfrac{\theta_{\mathsf{F}}}{\lambda_U\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}u)^2}\varphi(\lambda_U, u), & \text{if } 0 \le u < \frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}}, \\ 0, & \text{if } \frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}} \le u, \end{cases} \tag{25}$$

respectively, where $\varphi(\alpha, t) = \exp\big(-\frac{t}{\alpha\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)}\big)$, λ_U *represents the average channel power gain.*

Proof. The CDF of U can be written as:

$$F_U(u) = \Pr\big(\gamma\theta_{\mathsf{F}}\rho < (\gamma\theta_{\mathsf{N}}\rho+1)u\big). \tag{26}$$

After some basic manipulations, (26) can be rewritten as

$$F_U(u) = \Pr\left(\rho < \frac{u}{\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}u)}\right), \tag{27}$$

if $\rho < \frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}}$, otherwise, $F_U(u) = 1$. After some calculation steps, the PDF of U can be obtained as presented in equation (25). This completes the proof of Lemma 1. □

For the sake of notational convenience, let $Y_j \triangleq |h_{\mathsf{SF}_j}|^2$. After some algebra manipulations, Φ in (23) can be re-written as

$$\begin{aligned}\Phi &= \Pr\left(Y_j < \frac{\gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}t}{\gamma\big(\theta_{\mathsf{F}} - \theta_{\mathsf{N}}(\gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}t)\big)}\right) \\ &= \int_0^{\frac{\gamma_{\mathrm{th},\mathsf{F}_b}-1+\gamma_{\mathrm{th},\mathsf{F}_b}t}{\gamma[\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\gamma_{\mathrm{th},\mathsf{F}_b}-1+\gamma_{\mathrm{th},\mathsf{F}_b}t)]}} f_{Y_j}(y)dx \\ &= \begin{cases} 1-\varphi(\lambda_{\mathsf{SF}}, \gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}t), & \text{if } \frac{1}{\theta_{\mathsf{N}}\gamma_{\mathrm{th},\mathsf{F}_b}} - 1 > t, \\ 1, & \text{if } \frac{1}{\theta_{\mathsf{N}}\gamma_{\mathrm{th},\mathsf{F}_b}} - 1 \le t. \end{cases}\end{aligned} \tag{28}$$

By plugging (25) and (28) into (23), the $P_{\mathsf{SOP},\mathsf{F}_b}$ can be further expressed as:

$$\begin{aligned}&P_{\mathsf{SOP},\mathsf{F}_b} \\ &= \int_0^{\frac{1}{\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}}}-1}\prod_{j=1}^{M}\left[1-\varphi\Big(\lambda_{\mathsf{SF}}, \gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}t\Big)\right] \\ &\quad\times\frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)^2}\varphi(\lambda_{\mathsf{SE}}, t)dt \\ &\quad+\int_{\frac{1}{\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}}}-1}^{\frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}}}\frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)^2}\varphi(\lambda_{\mathsf{SE}}, t)dt.\end{aligned} \tag{29}$$

Similar to (20), we rely on the biniomial coefficient [15, eq. (1.111)]. Consequently, (29) can be further written as:

$$\begin{aligned}&P_{\mathsf{SOP},\mathsf{F}_b} \\ &= \int_0^{\frac{1}{\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}}}-1}\sum_{k=0}^{M}\binom{M}{k}(-1)^k \\ &\quad\times\exp\left(-\frac{k(\gamma_{\mathrm{th},\mathsf{F}_b}-1+\gamma_{\mathrm{th},\mathsf{F}_b}t)}{\lambda_{\mathsf{SF}}\gamma\big[\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\gamma_{\mathrm{th},\mathsf{F}_b}-1+\gamma_{\mathrm{th},\mathsf{F}_b}t)\big]}\right) \\ &\quad\times\frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)^2}\exp\left(-\frac{t}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)}\right)dt \\ &\quad+\int_{\frac{1}{\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}}}-1}^{\frac{\theta_{\mathsf{F}}}{\theta_{\mathsf{N}}}}\frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)^2}\exp\left(-\frac{t}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}t)}\right)dt.\end{aligned} \tag{30}$$

To the best of the authors' knowledge, it is very difficult to obtain the exact closed-form expression of (30). Thus, in this paper, we approximate (30) using Gaussian-Chebyshev quadrature [16, eq. (25.4.38)]. First, to utilize the Gaussian-Chebyshev quadrature, the range of (30) can be coordinated as:

$$\begin{aligned}&P_{\mathsf{SOP},\mathsf{F}_b} \\ &= \beta_1\int_{-1}^{1}\sum_{k=0}^{M}\binom{M}{k}(-1)^k \\ &\quad\times\exp\left(-\frac{k(\gamma_{\mathrm{th},\mathsf{F}_b}-1+\gamma_{\mathrm{th},\mathsf{F}_b}(\beta_1x+\beta_1)))}{\lambda_{\mathsf{SF}}\gamma\big[\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\gamma_{\mathrm{th},\mathsf{F}_b}-1+\gamma_{\mathrm{th},\mathsf{F}_b}(\beta_1x+\beta_1))\big]}\right) \\ &\quad\times\frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\beta_1x+\beta_1))^2} \\ &\quad\times\exp\left(-\frac{\beta_1x+\beta_1}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\beta_1x+\beta_1))}\right)dx \\ &\quad+\beta_2\int_{-1}^{1}\frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\beta_2x+\beta_3))^2} \\ &\quad\times\exp\left(-\frac{\beta_2x+\beta_3}{\lambda_{\mathsf{SE}}\gamma(\theta_{\mathsf{F}}-\theta_{\mathsf{N}}(\beta_2x+\beta_3))}\right)dx,\end{aligned} \tag{31}$$

where $\beta_1 = \frac{(1/\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}})-1}{2}$, $\beta_2 = \frac{(\theta_{\mathsf{F}}/\theta_{\mathsf{N}})-(1/\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}})+1}{2}$, $\beta_3 = \frac{(\theta_{\mathsf{F}}/\theta_{\mathsf{N}})+(1/\gamma_{\mathrm{th},\mathsf{F}_b}\theta_{\mathsf{N}})-1}{2}$. Next, to approximate, (31) can be

$$P_{\mathsf{SOP},\mathsf{F}_b} = \beta_1 \sum_{i=1}^{N} \frac{\pi}{N} \sqrt{1-\tau_i^2} \sum_{k=0}^{M} \binom{M}{k} (-1)^k \exp\left(- \frac{k(\gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}(\beta_1\tau_i + \beta_1))}{\lambda_{\mathsf{SF}}\gamma\left[\theta_{\mathsf{F}} - \theta_{\mathsf{N}}\left(\gamma_{\mathrm{th},\mathsf{F}_b} - 1 + \gamma_{\mathrm{th},\mathsf{F}_b}(\beta_1\tau_i + \beta_1)\right)\right]} \right)$$
$$\times \frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma\left[\theta_{\mathsf{F}} - \theta_{\mathsf{N}}(\beta_1\tau_i + \beta_1)\right]^2} \exp\left(- \frac{\beta_1\tau_i + \beta_1}{\lambda_{\mathsf{SE}}\gamma\left[\theta_{\mathsf{F}} - \theta_{\mathsf{N}}(\beta_1\tau_i + \beta_1)\right]} \right) \tag{32}$$
$$+ \beta_2 \sum_{i=1}^{N} \frac{\pi}{N} \sqrt{1-\tau_i^2} \frac{\theta_{\mathsf{F}}}{\lambda_{\mathsf{SE}}\gamma\left[\theta_{\mathsf{F}} - \theta_{\mathsf{N}}(\beta_2\tau_i + \beta_3)\right]^2} \exp\left(- \frac{\beta_2\tau_i + \beta_3}{\lambda_{\mathsf{SE}}\gamma\left[\theta_{\mathsf{F}} - \theta_{\mathsf{N}}(\beta_2\tau_i + \beta_3)\right]} \right),$$

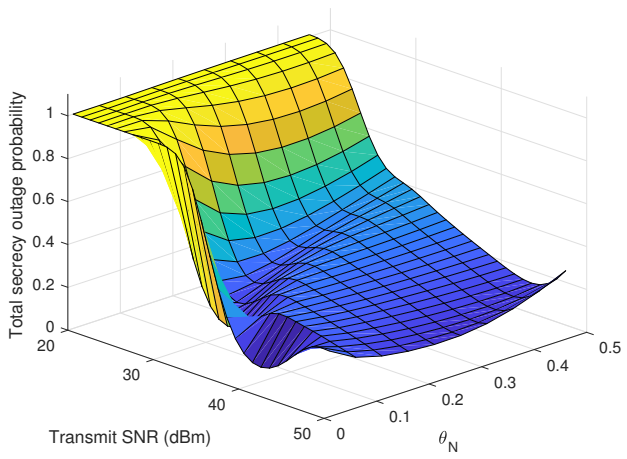

Fig. 2. The total SOP of the selected user pair as a function of transmit power and power allocation coefficient of the near user, θ_{N}, with $K = 3$, $M = 3$.

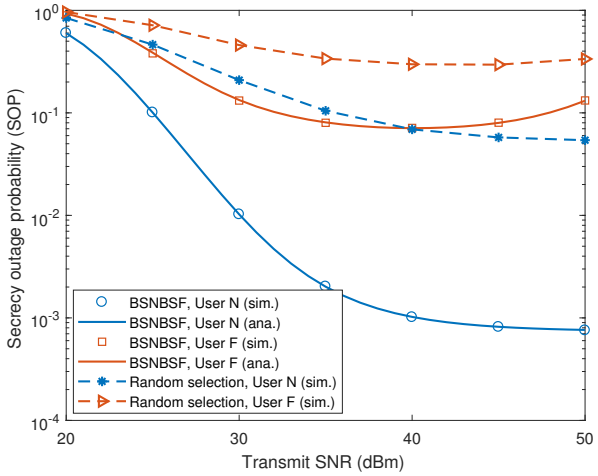

Fig. 3. Performance comparison between the proposed BSNBSF scheme and the random near user and random far user selection (RNRF) scheme with secrecy outage probability as a function of the transmit power, where $K = 3$, $M = 3$, $\gamma_{\mathrm{th},\mathsf{F}_b} = \gamma_{\mathrm{th},\mathsf{N}_b} = 0.1$ bps/Hz.

transformed using the fact that

$$\int_{-1}^{1} \frac{f(x)\sqrt{1-x^2}}{\sqrt{1-x^2}} dx = \sum_{i=1}^{N} w_i \sqrt{1-x_i^2} f(x_i),$$

where $w_i = \frac{\pi}{N}$, $x_i = \cos\left(\frac{2i-1}{N}\pi\right)$, and N is the number of term, respectively. The SOP of the selected far user can be approximated and in (32).

IV. Numerical Results

In this section, we present the representative numerical results of the SOP of the proposed scheme. Monte-Carlo simulation results are generated to validate the developed analysis. In simulation setting, we assume that position of the source S, the cluster of near users, the cluster of far users, and the eavesdropper E are randomly deployed satisfying some given distance constraints. Specifically, we set that the distance between S and the cluster near users is $d_{\mathsf{SN}} = 10$m, the distance between S and the cluster of far users is $d_{\mathsf{SF}} = 20$m, and that the distance between S and eavesdropper is $d_{\mathsf{SE}} = 30$m, respectively. It is noted that although multiple near or far users are located at the same location, their channel characteristics are different from one to another. Additional, the reference distance $d_0 = 1$m, and power degradation at d_0 is $L = 30$ (dB), the path-loss exponent $\epsilon = 2.7$.

We first investigate the effect of power allocation mechanism on the secrecy performance of the proposed scheduling scheme as shown in fig. 2, where the total SOP as in [9], [10] of selected user pair is plotted as a function of transmit power and power allocation coefficient of the near user, θ_{N}. It is noted that $\theta_{\mathsf{F}} = 1 - \theta_{\mathsf{N}}$. As can be observed, the total SOP poses a complicated convex characteristic with respect to θ_{N}. Specifically, the total SOP is a convex function with respect to θ_{N} when the transmit SNR is less than 30 (dBm) or greater than 45 dBm under our setting, while it is not a convex function when the transmit SNR is in the range from 30 to 45 dBm. Hence, finding an optimal value of θ_{N} that minimizes the total SOP is intractable. Therefore, in this section, we adopted fixed power allocation mechanism for the NOMA transmission. Specifically, the power allocation efficients are set as $\theta_{\mathsf{N}} = 0.2$, $\theta_{\mathsf{F}} = 0.8$. It is noteworthy that this setting has been widely adopted in the literature [3], [4], [6].

Fig. 3 presents the performance comparison of the BSNBSF scheme and random near and random far (RNRF) scheme, in which the number of the near users are 3, and the far users are 3, respectively. As can be seen in Fig. 3, the SOP of the BSNBSF scheme is lower than the that of random selection scheme. The reason is that the proposed scheme considers

the secrecy channel capacity to select the near user and far user, respectively. When the increasing the transmit power, the SOP of the selected near user increased until it reaches a performance floor. Different from the case of the selected near user, the SOP of the selected far user is plotted as in convex pattern with respect to the transmit SNR.

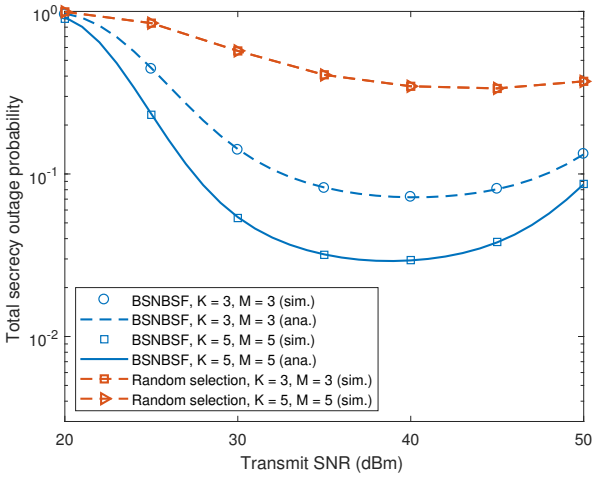

Fig. 4. Illustration of the impact of the number of near user and far user as a function of the transmit power, where $\gamma_{\mathrm{th},\mathrm{F}_b} = \gamma_{\mathrm{th},\mathrm{N}_b} = 0.1$ bps/Hz.

Fig. 4 illustrates the impact of the transmit SNR and the number of near and far users on the performance of the proposed scheduling scheme. As we can be seen in Fig.4, increasing the number of near and far users does not improve the performance of the RNRF scheme. In contrast to, when the number of the near and far users is higher, the performance of the proposed scheme is improved. Since the BSNBSF scheme exploits the difference in channel conditions between users to select the best near and far users pair.

From the Figs. 3 and 4, it can be observed that the proposed scheme achieves its best performance when an appropriate transmit SNR is used. If we use higher transmit SNR than the optimal level, the total SOP is worse, which leads to a waste of transmit power.

V. Conclusion

In this paper, we have investigated the secrecy performance of opportunistic scheduling in multi-near user and multi-far user NOMA system. We have proposed the BSNBSF scheme, which aims to improve the physical layer security of the considered NOMA system. More specifically, the proposed scheme selects the users by exploiting both main and eavesdropper channel characteristics to select the most robust near and far users. We have derived the exact closed-form expression for the SOP of the selected near user and the tight approximated closed-form expression for the SOP of the selected far user, which have been verified by the computer simulation. Our results showed that the proposed scheme provided a better secrecy performance compared to random near user and random far user selection scheme. Also, increasing number of participant near and/or far users improves the robustness of the proposed scheduling scheme.

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References

[1] NTT DOCOMO, "5G radio access: Requirements, concept and technologies," *White Paper*, June 2014.

[2] T. Shimojo, A. Umesh, D. Fujishima, and A. Minokuchi, "Special articles on 5G technologies toward 2020 deployment," *NTT DOCOMO Tech. J.*, vol. 17, no. 4, pp. 50–59, 2016.

[3] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, October 2017.

[4] T. N. Do, D. B. da Costa, T. Q. Duong, and B. An, "Improving the performance of cell-edge users in NOMA systems using cooperative relaying,," *IEEE Trans. Commun.*, 2018, DOI: 10.1109/TCOMM.2018.2796611.

[5] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, Dresden, Germany, June 2013, pp. 1–5.

[6] N. T. Do, D. B. D. Costa, T. Q. Duong, and B. An, "A BNBF user selection scheme for NOMA-based cooperative relaying systems with SWIPT," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 664–667, March 2017.

[7] N. Yang, L. Wang, G. Geraci, M. Elkashlan, J. Yuan, and M. Di Renzo, "Safeguarding 5g wireless communication networks using physical layer security," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 20–27, 2015.

[8] H. Lei, J. Zhang, K. H. Park, P. Xu, I. S. Ansari, G. Pan, B. Alomair, and M. S. Alouini, "On secure NOMA systems with transmit antenna selection schemes," *IEEE Access*, vol. 5, pp. 17 450–17 464, August 2017.

[9] Z. Qin, Y. Liu, Z. Ding, Y. Gao, and M. Elkashlan, "Physical layer security for 5G non-orthogonal multiple access in large-scale networks," in *2016 IEEE International Conference on Communications (ICC)*, May 2016, pp. 1–6.

[10] Y. Liu, Z. Qin, M. Elkashlan, Y. Gao, and L. Hanzo, "Enhancing the physical layer security of non-orthogonal multiple access in large-scale networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1656–1672, March 2017.

[11] K. Shim, T. N. Do, and B. An, "Performance analysis of physical layer security of opportunistic scheduling in multiuser multirelay cooperative networks," *Sensors*, vol. 17, no. 2, 2017.

[12] N. T. Do, D. B. da Costa, T. Q. Duong, V. N. Q. Bao, and B. An, "Exploiting direct links in multiuser multirelay SWIPT cooperative networks with opportunistic scheduling," *IEEE Trans. Wireless Commun.*, vol. 16, no. 8, pp. 5410–5427, August 2017.

[13] T. M. Cover and J. A. Thomas, *Elements of information theory*. John Wiley & Sons, 2012.

[14] K. Shim, N. T. Do, B. An, and S. Y. Nam, "Outage performance of physical layer security for multi-hop underlay cognitive radio networks with imperfect channel state information," in *2016 International Conference on Electronics, Information, and Communications (ICEIC)*, Da Nang, Vietnam, January 2016, pp. 1–4.

[15] I. Gradshteyn and I. Ryzhik, *Table of Integrals, Series, and Products (7th edition)*. Academic Press is an imprint of Elsevier, 2007.

[16] M. Abramowitz and I. A. Stegun, *Handbook of mathematical functions: with formulas, graphs, and mathematical tables*. Courier Corporation, 1964, vol. 55.