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# Antenna Mode Switching for Full-Duplex Destination-Based Jamming Secure Transmission

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**ABSTRACT** We investigate the secrecy rate optimization problem in a wiretap channel with a single-antenna source, a single-antenna eavesdropper, and a multiple-antenna full-duplex (FD) destination. To fully utilize the spatial degrees-of-freedom of multiple antennas, the function of antennas at the destination is not predefined, i.e., each antenna can operate in a transmit or receive mode. We propose a low-complexity near-optimal joint optimization scheme by jointly applying the dynamic antenna mode switching (AMS) and optimal power allocation (OPA) techniques, to maximize the secrecy rate of the FD destination-based jamming (DBJ) system. The proposed joint optimization scheme is valid for two different eavesdropping channel state information (ECSI) availability cases, i.e., instantaneous ECSIs and statistical ECSIs. Specifically, closed-form expressions of OPA factors are first derived, and then the optimal transmit and receive antennas sets at the destination are determined by combining the OPA factor and applying a greedy-search-based AMS approach for both ECSIs availabilities, respectively. Moreover, through complexity analysis, the search complexity of the proposed scheme is proven to be significantly reduced compared with the exhaustive searching method. Simulation results verify the secrecy performance superiority of the proposed scheme over the conventional FD-DBJ method.

**INDEX TERMS** Physical layer security, antenna mode switching, full duplex, destination-based jamming, optimal power allocation.

## I. INTRODUCTION

Physical layer security has become a promising technique to guarantee the secure transmission by directly exploiting the randomness offered by wireless channels [1], [2]. Wyner originally presented the concept of physical layer security (PLS) for the wiretap model in [3]. In recent years, to enhance the secrecy performance of system, several schemes have been proposed, such as cooperative jamming (CJ), by introducing the jamming signal to interfere the reception of the eavesdropper [4]. As an efficient CJ strategy, the destination-based jamming (DBJ) scheme allows the destination node to emit the artificial noise (AN), to reduce the probability of being intercepted without affecting the transmission quality of legitimate channel [5]. Moreover, the DBJ scheme is more reliable and easier to implement compared with the CJ scheme using external helpers.

The loop-interference (LI), which is a strong interfering signal from the transmit antenna to the receive antenna at the full-duplex (FD) node, makes the FD node suffer from significant attenuation. Fortunately, thanks to recent progress in loop-interference cancellation (LIC) technique, the LI can be suppressed up to $-110$dB [6], that makes the FD system more practical. The passive cancellation approaches can suppress LI by using path loss, cross polarization, antenna directionality or the combinations of them [7], [8], while the active methods apply the knowledge of LI to cancel the interference in analog or digital domain [9], [10].

When the destination operates in the FD mode in the wiretap channel, to achieve better secrecy performance, the FD-DBJ scheme was proposed to allow the destination to receive the information signal and simultaneously to send the AN to interfere the eavesdropper [11]–[15]. In [11], the FD-DBJ scheme was originally proposed and has been proven to have several practical advantages compared to the scheme that AN is sent by the source. In [12], the FD-DBJ was extended to the situation of two FD destinations combining the CJ from the source, and an optimization problem considering the statistical eavesdropping channel state information (ECSI) to maximize the secrecy sum-rate was solved. In a multiple-input multiple-output (MIMO) wiretap channel with instantaneous ECSI known by the legitimate system, to achieve the maximal secure degrees of freedom (S.D.o.F.) for the FD-DBJ scheme, the optimal antenna allocation at the destination and the precoding matrices were designed in [13]. In [14], for a general MIMOME wiretap channel with multiple multi-antenna destinations and eavesdroppers, the secrecy rate was optimized by taking into consideration the AN generated by both the source and the FD destinations, where the perfect ECSI is assumed known by the legitimate nodes. In a SIMO wiretap channel, the joint transmit and receive beamforming design is optimized for the FD-DBJ scheme in [15] considering the effect of LI.

For the multiple-antenna FD node, when the function of each antenna is not predefined, i.e., the antenna can operate either in transmit mode or in receive mode, the system performance can be greatly improved by dynamic antenna mode switching (AMS) technique, compared with the fixed-mode antennas, i.e., the function of each antenna is predefined. In [16], the AMS was jointly optimized with power splitting factor, to maximize the achievable rate of simultaneous wireless information and power transfer (SWIPT) system. In bidirectional FD systems, a transmit-receive antenna pair selection strategy using AMS was designed based on maximum sum rate and minimum symbol error rate respectively in [17]. Considering the general MIMO transmission scenario, an AMS method for bidirectional FD MIMO systems was proposed to improve the sum rate performance in [18]. In [19], a joint AMS at the relay and opportunistic source selection strategy was presented to improve the FD relay system performance. In [13], although the antenna allocation was optimized at the FD jamming destination, the aim of analysis was to achieve the maximal S.D.o.F. from the perspective of whole system and did not consider the transmit/receive functionality of a specific antenna. In the MIMO wiretap channel with FD-DBJ, the joint optimization of beamforming, antenna allocation, and power allocation was analyzed in [6], however the closed-form expression of the power allocation factor was not provided for specific antenna allocation.

In this paper, we aim to optimize the FD-DBJ scheme in a wiretap system with multiple-antenna destination. Different from the fixed mode antennas at the FD jamming destination [11], [14], [15], our model considers a multiple-antenna destination which dynamically selects a set of antennas to transmit AN and the remaining antennas to receive the information signal by utilizing the AMS strategy. Hence, it is challenging to find the feasible antenna sets and jointly design the optimal power allocation (OPA) factor with the total transmit power constraint of source and destination. Achievable secrecy rate will be the performance metric to derive the OPA factor and design the AMS algorithm. The main contributions of this paper are summarized in the following.

- To obtain the maximal achievable secrecy rate, we propose a low-complexity two-step optimization scheme by applying the greedy-search-based AMS and the OPA techniques for the FD-DBJ system.
- For two cases of ECSIs availablity, i.e., instantaneous ECSIs and statistical ECSIs, closed-form expressions of the OPA factors are derived respectively, by discussing the convexity and using the Karush-Kuhn-Tucker (KKT) conditions with any feasible transmit/receive antenna set, which is applicable for both fixed-mode and dynamic-mode antennas at FD destination.
- To show the complexity advantage of the proposed scheme, the complexity analysis is performed by comparing with the optimal exhaustive search method. Simulation results show that, the performance of the proposed scheme is superior to the FD-DBJ with fixed-mode antennas, and approaches the optimal scheme with much lower complexity. Moverover, the AMS algorithm and the OPA technique in the proposed scheme are indenpendent to each other and can provide a certain performance gain separately.

The rest of this paper is organized as follows. In section II, we introduce the system model and the FD-DBJ transmission scheme. Section III presents a joint optimization scheme for the two ECSIs availabilities and the complexity analysis. Section IV shows the numerical results and discussions. Section V concludes the paper.

*Notation:* We use $(\cdot)^T$ for transpose, $(\cdot)^H$ for Hermitian transpose, $\mathbb{E}\{\cdot\}$ for mathematical expectation, $|\cdot|$ for modulo operator, $\|\cdot\|$ for the Frobenius norm, and $\mathcal{CN}\left(\mu, \sigma^2\right)$ for the complex Gaussian distribution with mean $\mu$ and variance $\sigma^2$. Bold lower case letters denote vectors, e.g., $\mathbf{v}$.

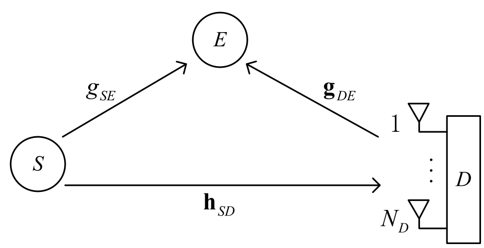


**FIGURE 1.** System model of the FD-DBJ secure transmission with multiple-antenna destination.

## II. SYSTEM MODEL

Fig. 1 shows a full-duplex secure transmission model, which is composed of one source ($S$), one full-duplex destination ($D$), and one eavesdropper ($E$). The number of antennas at $S$, $D$, and $E$ is 1, $N_D$, and 1, respectively. Denote $\mathbb{A}_T$ and $\mathbb{A}_R$ as the sets of $N_{Dt}$ transmit antennas and $N_{Dr}$ receive antennas respectively, with $N_{Dt} + N_{Dr} = N_D$, where $N_D$ represents the total number of antennas at $D$. The channels $S \to D$, $S \to E$, and $D \to E$ are denoted as $\mathbf{h}_{SD} = \left[h_{S1}, h_{S2}, \cdots, h_{SN_{Dr}}\right]^T$, $g_{SE}$, and $\mathbf{g}_{DE} = \left[g_{1E}, g_{2E}, \cdots, g_{N_{Dt}E}\right]$ respectively, where $h_{Si}$ is the channel coefficient between $S$ and the $i$-th receive antenna in $\mathbb{A}_R$, and $g_{jE}$ represents the channel coefficient between the $j$-th transmit antenna in $\mathbb{A}_T$ and $E$ with $i = 1, \cdots, N_{Dr}$, and $j = 1, \cdots, N_{Dt}$. All links are modeled as block Rayleigh fading channels, i.e., the channel remains static for one coherence interval and changes independently in different coherence intervals. All the channel coefficients are independent zero-mean circularly symmetric complex Gaussian (ZMCSCG) random variables, and average channel power gains are separately modeled as $\mathbb{E}\left\{|h_{Si}|^2\right\} = \Omega_{SD}$, $\mathbb{E}\left\{|g_{jE}|^2\right\} = \Omega_{DE}$, and $\mathbb{E}\left\{|g_{SE}|^2\right\} = \Omega_{SE}$. In this paper, we denote the transmit power of $S$ and $D$ as $P_S$ and $P_D$, respectively, with the total power constraint $P_S + P_D = P$, where $P_S = \alpha P$, $P_D = (1-\alpha)P$, and $\alpha$ is the power allocation factor. It should be noted that the total transmit power constraint is widely used in the power-limited networks [5], [15], [20], [21].

The legitimate nodes are assumed to be aware of the instantaneous CSI of the main channel, i.e., channel $S \to D$. According to the existing works that study PLS, the legitimate nodes are assumed to know the presence of the eavesdropper by applying the detection technique in [22], and can acquire a certain degree of ECSI. This paper considers two different circumstances for the ECSIs availability at the legitimate nodes as follows:

- *Instantaneous ECSIs Case:* The legitimate nodes are aware of the instantaneous ECSIs, which is a common assumption in the PLS works [23]–[26]. This is possible in the situations where the eavesdropper is normally an active member on the network (registered but not authorized on the network) and communicates with other nodes, the eavesdropper's CSI can be collected by the legitimate nodes through feedback links [27].
- *Statistical ECSIs Case:* The statistical ECSIs, i.e., the average values of eavesdropping channel gains, are known by the legitimate nodes [28], [29]. In the case that the eavesdropper is a malicious node, the statistical ECSIs can be collected by the legitimate nodes through long-term monitoring [28].

Based on the FD-DBJ strategy, as the source transmits the message, the destination transmits the AN to jam the eavesdropper using $N_{Dt}$ antennas, and the remaining $N_{Dr}$ antennas are used for reception. By applying LIC techniques, it is possible for $D$ to eliminate the LI to the noise level [6]. Hence, we do not consider the LI at $D$ in this paper. This is a widely used consideration when the information-theory oriented performance limit is studied [6], [11], [30], [31], though complete LIC cannot even be achieved with the state-of-the-art techniques [32]. To maximize the received signal, the maximum ratio combining (MRC) scheme is applied at the receive antennas of $D$, and the data estimate at $D$ can be calculated as

$$y_D = \frac{\mathbf{h}_{SD}^H}{\|\mathbf{h}_{SD}\|}\left(\mathbf{h}_{SD}x_S + \mathbf{n}_D\right) = \|\mathbf{h}_{SD}\|\, x_S + \frac{\mathbf{h}_{SD}^H\mathbf{n}_D}{\|\mathbf{h}_{SD}\|}, \tag{1}$$

where $x_S\, \mathcal{CN}(0, \alpha P)$ denotes the source signal emitted from S and $\mathbf{n}_D \sim \mathcal{CN}(0, \mathbf{I})$ is the additive white Gaussian noise (AWGN) at $D$.

In the case that the instantaneous ECSIs are known by the legitimate node. The AN emitted from the transmit antennas at $D$ is designed as $v$, which is a complex Gaussian random variable with zero mean and variance $\sigma_v^2 = (1-\alpha)P$. To maximize the interfering effect of the AN signal, $D$ applies the maximum ratio transmission (MRT) technique to broadcast the AN signal. The received signal at $E$ is given by

$$y_E^I = g_{SE}x_S + \mathbf{g}_{DE}\frac{\mathbf{g}_{DE}^H}{\|\mathbf{g}_{DE}\|}v + n_E = g_{SE}x_S + \|\mathbf{g}_{DE}\|\, v + n_E, \tag{2}$$

where $n_E \sim \mathcal{CN}(0, 1)$ denotes the AWGN at $E$ and the superscript '$I$' indicates "instantaneous ECSIs".

In the case that the legitimate nodes are only aware of the statistical ECSIs, the MRT technique at $D$ can not be applied any more. $D$ sorely emits the AN without any beamforming strategies and the AN signal is designed as $\mathbf{v} \in \mathbb{C}^{N_{Dt}\times 1}$. We note that each element of the AN vector $\mathbf{v}$ is an i.i.d. complex Gaussian random variable with variance $\sigma_v^2 = \frac{(1-\alpha)P}{N_{Dt}}$ due to the equal distribution of the transmit power among the $N_{Dt}$ artificial noise elements. The received signal at $E$ can be expressed as

$$y_E^S = g_{SE}x_S + \mathbf{g}_{DE}\mathbf{v} + n_E, \tag{3}$$

where the superscript '$S$' means "statistical ECSIs".

Based on (1), (2) and (3), the received signal-to-noise ratio (SNR) at $D$ and $E$ can be calculated respectively as

$$\gamma_D = \alpha P \gamma_{SD}^{\mathbb{A}_R}, \tag{4}$$

$$\gamma_E^I = \begin{cases} \dfrac{\alpha P \gamma_{SE}}{(1-\alpha)P\gamma_{DE}^{\mathbb{A}_T} + 1}, & N_{Dt} \geq 1 \\ P\gamma_{SE}, & N_{Dt} = 0 \end{cases}, \tag{5}$$

$$\gamma_E^S = \begin{cases} \dfrac{\alpha P \gamma_{SE}}{\frac{(1-\alpha)P}{N_{Dt}}\gamma_{DE}^{\mathbb{A}_T} + 1}, & N_{Dt} \geq 1 \\ P\gamma_{SE}, & N_{Dt} = 0 \end{cases}, \tag{6}$$

where $\gamma_{SD}^{\mathbb{A}_R} = \sum_{i=1}^{N_{Dr}} |h_{Si}|^2$, $\gamma_{DE}^{\mathbb{A}_T} = \sum_{j=1}^{N_{Dt}} |g_{jE}|^2$ and $\gamma_{SE} = |g_{SE}|^2$. Notice that, in the case of $N_{Dt} = 0$ for both considered ECSIs availabilities, $D$ has no antenna to broadcast AN. Thus, all the transmit power of the system should be allocated to $S$, i.e., $\alpha = 1$. Furthermore, we have $\gamma_E^I = \gamma_E^S = P\gamma_{SE}$ for $N_{Dt} = 0$.

## III. SECRECY PERFORMANCE ANALYSIS

In this section, we will investigate the maximization of the achievable secrecy rate for each of the two ECSIs availability circumstances through the joint optimization of AMS and OPA.

### A. THE OPA SCHEME FOR INSTANTANEOUS ECSIs

In the instantaneous ECSIs case, the achievable secrecy rate can be expressed as [33], [34]

$$\begin{aligned} R_S^I &= \max\left\{0, R_D - R_E^I\right\} \\ &= \max\left\{0, \log_2(1+\gamma_D) - \log_2\left(1+\gamma_E^I\right)\right\} \\ &= \max\left\{0, \log_2\left(\Lambda^I\right)\right\}, \end{aligned} \tag{7}$$

where

$$\Lambda^I = \frac{1+\gamma_D}{1+\gamma_E^I}. \tag{8}$$

Consequently, to maximize the achievable secrecy rate of the considered system in the instantaneous ESCIs circumstance, the optimization problem $P1$ can be expressed as

$$\begin{aligned} (P1): \quad & \max_{\alpha, \mathbb{A}_T, \mathbb{A}_R} \log_2\left(\Lambda^I\right) \\ & s.t.\ 0 \le \alpha \le 1, \\ & \quad N_{Dr} \ge 1, \\ & \quad N_{Dt} \ge 0, \\ & \quad N_{Dt} + N_{Dr} = N_D. \end{aligned} \tag{9}$$

Since log is an increasing function, Problem $P1$ is equivalent to Problem $P2$ for given feasible antenna sets [35] as follows:

$$\begin{aligned} (P2): \quad & \max_{\alpha, \mathbb{A}_T, \mathbb{A}_R} \Lambda^I \\ & s.t.\ 0 \le \alpha \le 1, \\ & \quad N_{Dr} \ge 1, \\ & \quad N_{Dt} \ge 0, \\ & \quad N_{Dt} + N_{Dr} = N_D. \end{aligned} \tag{10}$$

It is worthy to note that Problem $P2$ is non-linear and convexity-undetermined with respect to (w.r.t.) $\alpha$ as shown in *Theorem 1* which will be clearly stated at the end of this subsection. To make Problem $P2$ tractable, a two-step optimization scheme is presented, where the feasible antenna sets are fixed in the first place to obtain the OPA factor $\alpha_{\mathbb{A}_T}^{I*}$, and then the AMS procedure is designed. The following lemma is provided to help the derivation of the OPA factor in the circumstance of instantaneous ECSIs.

*Lemma 1:* For given antenna sets (i.e., AMS solutions) and in the case of instantaneous ECSIs, when $\gamma_{SE} \le \gamma_{SD}^{\mathbb{A}_R}$, the positive secrecy rate can always be achieved for any $0 < \alpha \le 1$, and the achievable secrecy rate (7) can be expressed as

$$R_S^I = \log_2\left(\Lambda^I\right), \quad 0 \le \alpha \le 1. \tag{11}$$

When $\gamma_{SD}^{\mathbb{A}_R} < \gamma_{SE} < \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R}$, the achievable secrecy rate can be expressed as

$$R_S^I = \begin{cases} 0, & 1 + \dfrac{\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}}{P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}} < \alpha \le 1 \\ \log_2\left(\Lambda^I\right), & 0 \le \alpha \le 1 + \dfrac{\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}}{P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}}. \end{cases} \tag{12}$$

When $\gamma_{SE} \ge \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R}$, the achievable secrecy rate $R_S^I = 0$ for all $0 \le \alpha \le 1$.

For $N_{Dt} = 0$, in the case of $\gamma_{SE} < \gamma_{SD}^{\mathbb{A}_R}$, we get $R_S^I = \log_2\left(\Lambda^I\right)$. In the case of $\gamma_{SE} \ge \gamma_{SD}^{\mathbb{A}_R}$, $R_S^I = 0$.

*Proof:* In the circumstance of instantaneous ECSIs, for given AMS solutions, the positive secrecy rate can be always achieved if and only if $\Lambda^I$ is strictly greater than 1, i.e., $\gamma_D > \gamma_E^I$. Furthermore, we have

$$\alpha P \gamma_{SD}^{\mathbb{A}_R} > \frac{\alpha P \gamma_{SE}}{(1-\alpha)P\gamma_{DE}^{\mathbb{A}_T} + 1}. \tag{13}$$

The above inequality can be reformulated as

$$\alpha < 1 + \frac{\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}}{P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}}. \tag{14}$$

In the case of $\gamma_{SE} \le \gamma_{SD}^{\mathbb{A}_R}$, (14) holds true for $0 < \alpha \le 1$, so the positive secrecy rate is always achieved.

In order to meet the condition $\alpha \ge 0$, the right part of (14) should be limited as

$$1 + \frac{\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}}{P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}} > 0, \tag{15}$$

and we obtain $\gamma_{SE} < \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R}$.

In the case of $\gamma_{SD}^{\mathbb{A}_R} < \gamma_{SE} < \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R}$, the positive secrecy rate can only be achieved for $0 \le \alpha \le 1 + \left(\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}\right) / \left(P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}\right)$, and is forced to zero for $1 + \left(\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}\right) / \left(P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}\right) < \alpha \le 1$ according to (7).

In the case of $\gamma_{SE} \ge P\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T} + \gamma_{SD}^{\mathbb{A}_R}$, the condition $\alpha \ge 0$ can not be met, thus the positive secrecy rate can not be achieved for $0 < \alpha \le 1$, and we get $R_S^I = 0$ for $0 \le \alpha \le 1$.

When $N_{Dt} = 0$, the similar conclusion can be obtained. ■

In the case of instantaneous ECSIs, the following theorem provides the OPA factor for given AMS solutions.

*Theorem 1:* For given AMS solutions under instantaneous ECSIs condition, (8) is a concave function w.r.t. $\alpha$ for $\Gamma \le 0$, and is a convex function for $\Gamma > 0$, where $\Gamma = \gamma_{SE} - \left(\gamma_{DE}^{\mathbb{A}_T} + \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P\right)$. The OPA factor for $N_{Dt} \ge 1$ is expressed as (17), shown at the top of the next page, where

$$\begin{aligned} \Psi = & \sqrt{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}\gamma_{SE}P^2\left(1+\gamma_{DE}^{\mathbb{A}_T}P\right)} \\ & \times \sqrt{\gamma_{DE}^{\mathbb{A}_T} + \gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P}. \end{aligned} \tag{16}$$

*Proof:* Please see the appendix. ■

### B. THE OPA SCHEME FOR STATISTICAL ECSIs

In the case of statistical ECSIs, due to the absence of the instantaneous ECSIs, the instantaneous eavesdropping rate, i.e., $\log_2\left(1+\gamma_E^I\right)$ can not be obtained. However, we can get the ergodic eavesdropping rate which can be written as

$$R_E^S = \mathbb{E}_{\gamma_{SE}, \gamma_{DE}^{\mathbb{A}_T}}\left[\log_2\left(1 + \frac{\alpha P \gamma_{SE}}{\frac{(1-\alpha)P}{N_{Dt}}\gamma_{DE}^{\mathbb{A}_T} + 1}\right)\right]. \tag{18}$$

$$\alpha_{\mathbb{A}_T}^{I*}=\begin{cases}\min\left(\dfrac{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P\left(1+P\gamma_{DE}^{\mathbb{A}_T}\right)-\Psi}{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P^2\left(\gamma_{DE}^{\mathbb{A}_T}-\gamma_{SE}\right)},1\right), & \gamma_{SE}<\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P+\gamma_{SD}^{\mathbb{A}_R}\&\gamma_{DE}^{\mathbb{A}_T}-\gamma_{SE}\neq 0\\ \min\left(\dfrac{1}{2}+\dfrac{\gamma_{SD}^{\mathbb{A}_R}-\gamma_{SE}}{2\gamma_{SD}^{\mathbb{A}_R}\gamma_{SE}P},1\right), & \gamma_{SE}<\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P+\gamma_{SD}^{\mathbb{A}_R}\&\gamma_{DE}^{\mathbb{A}_T}-\gamma_{SE}=0\\ \textit{No OPA factor for } \alpha\in[0,1], & \gamma_{SE}\geq\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P+\gamma_{SD}^{\mathbb{A}_R}\end{cases} \tag{17}$$

Because $\gamma_{DE}^{\mathbb{A}_T}$ is composed of isotropic Rayleigh-fading components, the different combinations of AN-transmitting antennas can only impact $R_E^S$ by $N_{Dt}$ on average. Hence, $R_E^S$ is relevant to the total number of transmit antennas at $D$ and is irrelevant to the specific combinations of AN-transmitting antennas. We note that $\gamma_{SE}\sim \mathrm{E}(1/\Omega_{SE})$ and $\gamma_{DE}^{\mathbb{A}_T}\sim\Gamma(N_{Dt},1/\Omega_{DE})$. However, the exact evaluation of (18) is mathematically intractable for our transmission system. Therefore, we focus on the upper bound of the ergodic eavesdropping rate in the case of $N_{Dt}\geq 1$, which is expressed as

$$\begin{aligned}R_E^S&=\mathbb{E}_{\gamma_{SE},\gamma_{DE}^{\mathbb{A}_T}}\left[\log_2\left(1+\frac{\alpha P\gamma_{SE}}{\frac{(1-\alpha)P}{N_{Dt}}\gamma_{DE}^{\mathbb{A}_T}+1}\right)\right]\\&\overset{(a)}{\leq}\mathbb{E}_{\gamma_{SE},\gamma_{DE}^{\mathbb{A}_T}}\left[\log_2\left(1+\frac{\alpha P\gamma_{SE}}{\frac{(1-\alpha)P}{N_{Dt}}\gamma_{DE}^{\mathbb{A}_T}}\right)\right]\\&\overset{(b)}{\leq}\log_2\left[1+\mathbb{E}_{\gamma_{SE},\gamma_{DE}^{\mathbb{A}_T}}\left(\frac{\alpha\gamma_{SE}}{\frac{1-\alpha}{N_{Dt}}\gamma_{DE}^{\mathbb{A}_T}}\right)\right]\\&=\tilde{R}_E^S,\end{aligned} \tag{19}$$

where (a) holds true because the worst case, i.e., $n_E\to 0$, is considered, and (b) holds true due to the concavity of logarithm function. Notice that, in the case of $N_{Dt}=0$, $D$ has no antenna to broadcast AN. Thus, all the transmit power of the system should be allocated to $S$, i.e., $\alpha=1$ and $\tilde{R}_E^S=\log_2\left[1+P\mathbb{E}_{g_{SE}}\left(|g_{SE}|^2\right)\right]$ for $N_{Dt}=0$. We note that when $N_{Dt}=1$, the exact evolution of $\tilde{R}_E^S$ is impossible to be obtained. Therefore, we calculate its approximation by taking expectation operations on each individual random terms as

$$\begin{aligned}&\log_2\left[1+\mathbb{E}_{\gamma_{SE},\gamma_{DE}^{\mathbb{A}_T}}\left(\frac{\alpha\gamma_{SE}}{(1-\alpha)\gamma_{DE}^{\mathbb{A}_T}}\right)\right]\\&\geq\log_2\left[1+\frac{\alpha\mathbb{E}_{\gamma_{SE}}(\gamma_{SE})}{(1-\alpha)\mathbb{E}_{\gamma_{DE}^{\mathbb{A}_T}}\left(\gamma_{DE}^{\mathbb{A}_T}\right)}\right]\\&=\log_2\left(1+\frac{\alpha\Omega_{SE}}{(1-\alpha)\Omega_{DE}}\right).\end{aligned} \tag{20}$$

This approximation is an lower bound of the original expression $\tilde{R}_E^S$ in the case of $N_{Dt}=1$ according to the Jeasen's Inequality.

In the circumstance of statistical ECSIs, the lower bound of achievable secrecy rate can be calculated as [36]

$$\begin{aligned}R_S^S&=\max\left\{0,R_D-\tilde{R}_E^S\right\}\\&=\max\left\{0,\log_2\left(\Lambda^S\right)\right\},\end{aligned} \tag{21}$$

where $\Lambda^S$ is defined as

$$\Lambda^S=\begin{cases}\dfrac{\left(1+\alpha P\gamma_{SD}^{\mathbb{A}_R}\right)(1-\alpha)(N_{Dt}-1)\Omega_{DE}}{(1-\alpha)(N_{Dt}-1)\Omega_{DE}+\alpha\Omega_{SE}N_{Dt}}, & N_{Dt}\geq 2\\ \dfrac{1+P\gamma_{SD}^{\mathbb{A}_R}}{1+P\Omega_{SE}}, & N_{Dt}=0\\ \dfrac{\left(1+\alpha P\gamma_{SD}^{\mathbb{A}_R}\right)(1-\alpha)\Omega_{DE}}{(1-\alpha)\Omega_{DE}+\alpha\Omega_{SE}}, & N_{Dt}=1.\end{cases} \tag{22}$$

In the case of statistical ECSIs, to maximize the lower bound of the achievable secrecy rate for the considered system, the optimization problem $P3$ can be written as

$$\begin{aligned}(P3):\quad&\max_{\alpha,\mathbb{A}_T,\mathbb{A}_R}\ \Lambda^S\\&s.t.\ 0\leq\alpha\leq 1,\\&\quad N_{Dr}\geq 1,\\&\quad N_{Dt}\geq 0,\\&\quad N_{Dt}+N_{Dr}=N_D.\end{aligned} \tag{23}$$

We note that Problem $P3$ is non-linear and convexity-uncertain w.r.t. $\alpha$ as shown in *Theorem 2* which is stated at the end of this subsection. To make Problem $P3$ solvable, a similar two-step optimization method as the solution for Problem $P2$ is applied. The following lemma is provided to help the derivation of the OPA factor in the case of statistical ECSIs.

*Lemma 2:* For given antenna sets, when $N_{Dt}\geq 2$ and in the case of $\gamma_{SD}^{\mathbb{A}_R}>N_{Dt}\Omega_{SE}/[(N_{Dt}-1)P\Omega_{DE}]$, the lower bound of the achievable secrecy rate can be calculated as (24), which is shown at the bottom of the next page. In the case of $\gamma_{SD}^{\mathbb{A}_R}\leq N_{Dt}\Omega_{SE}/[(N_{Dt}-1)P\Omega_{DE}]$, the condition $\alpha\geq 0$ cannot be met. Therefore, we obtain $R_S^S=0$ for $\alpha\in[0,1]$.

When $N_{Dt}=0$, in the case of $\gamma_{SD}^{\mathbb{A}_R}>\Omega_{SE}$, we get $R_S^S=\log_2\left(\Lambda^S\right)$. In the case of $\gamma_{SD}^{\mathbb{A}_R}\leq\Omega_{SE}$, $R_S^S=0$.

When $N_{Dt}=1$, in the case of $\Omega_{SE}\geq P\gamma_{SD}^{\mathbb{A}_R}\Omega_{DE}$, $R_S^S=0$, for $\alpha\in[0,1]$. In the case of $\Omega_{SE}<P\gamma_{SD}^{\mathbb{A}_R}\Omega_{DE}$, the lower

bound of the achievable secrecy rate can be calculated as

$$R_S^S = \begin{cases} \log_2\left[\dfrac{\left(1+\alpha P\gamma_{SD}^{\mathbb{A}_R}\right)(1-\alpha)\Omega_{DE}}{(1-\alpha)\Omega_{DE}+\alpha\Omega_{SE}}\right], & 0 \le \alpha \le 1-\dfrac{\Omega_{SE}}{P\Omega_{DE}\gamma_{SD}^{\mathbb{A}_R}} \\ 0, & 1-\dfrac{\Omega_{SE}}{P\Omega_{DE}\gamma_{SD}^{\mathbb{A}_R}} < \alpha \le 1. \end{cases} \quad (25)$$

*Proof:* The proof is similar to the proof of *Lemma 1*. For brevity, we omit it here. ■

In the case of statistical ECSIs, the following theorem provide the OPA factors for given AMS solutions.

*Theorem 2:* For given AMS solutions, the OPA factor in the case of statistical ECSIs is given by (26), shown at the bottom of the next page, where

$$\Upsilon = \sqrt{\gamma_{SD}^{\mathbb{A}_R} P N_{Dt}\Omega_{SE}} \times \sqrt{(N_{Dt}-1)\Omega_{DE}\left(1+\gamma_{SD}^{\mathbb{A}_R}P\right)-N_{Dt}\Omega_{SE}},$$

and $\Delta = \sqrt{\gamma_{SD}^{\mathbb{A}_R} P\Omega_{SE}\left[\Omega_{DE}\left(1+\gamma_{SD}^{\mathbb{A}_R}P\right)-\Omega_{SE}\right]}$.

*Proof:* The proof is presented in the appendix. ■

### C. THE EXHAUSTIVE SEARCHING AMS-OPA SCHEME

Based on *Theorem 1*, with feasible given antenna sets, combining (4), (5), (8), and (17), we obtain the optimization objective with the OPA factor as $\Lambda^I\left(\alpha_{\mathbb{A}_T}^{I*}\right)$. Since the number of the feasible antennas at the destination is finite in practice, we can use the exhaustive searching method to find the optimal antenna sets among all feasible AMS solutions with the determined OPA factor to maximize the achievable secrecy rate in the case of instantaneous ECSIs, and we refer to this scheme as ES-AMS-OPA. In the case of statistical ECSIs and according to *Theorem 2*, the optimization objective with the OPA factor, i.e., $\Lambda^S\left(\alpha_{\mathbb{A}_T}^{S*}\right)$, can be calculated, so the ES-AMS-OPA scheme can also be applied.

### D. THE PROPOSED AMS-OPA SCHEME

The proposed AMS-OPA scheme is summarized in Algorithm 1 and is valid for both considered ECSIs availabilities. For a given $\mathbb{A}_T$, the receive antenna set is determined by $\mathbb{A}_R = \{a_n \mid n \in [1, N_D], a_n \notin \mathbb{A}_T\}$, where $a_n$ is the label of antenna working in the receive mode among all the $N_D$ antennas at $D$, i.e., $\mathbb{A}_R$ is the complementary set of $\mathbb{A}_T$. Note that $card(\mathbb{A}_T) = N_{Dt}$, hence $card(\mathbb{A}_R) = N_D - N_{Dt}$, where $card(\cdot)$ represents the cardinality of a set. We denote that $\Lambda_{\mathbb{A}_T} \in \left\{\Lambda_{\mathbb{A}_T}^I\left(\alpha_{\mathbb{A}_T}^{I*}\right), \Lambda_{\mathbb{A}_T}^S\left(\alpha_{\mathbb{A}_T}^{S*}\right)\right\}$, which means $\Lambda_{\mathbb{A}_T}$ represents either $\Lambda_{\mathbb{A}_T}^I\left(\alpha_{\mathbb{A}_T}^{I*}\right)$ or $\Lambda_{\mathbb{A}_T}^S\left(\alpha_{\mathbb{A}_T}^{S*}\right)$ for $card(\mathbb{A}_T)$ transmit antennas. We denote the largest $\Lambda_{\mathbb{A}_T}$ as

$$\Lambda_{\mathbb{A}_T}^{max} = \max_{\mathbb{A}_T}\Lambda_{\mathbb{A}_T}. \quad (27)$$

We initialize the transmit antenna set as an empty set, i.e., $\mathbb{A}_T^{opt} = \emptyset$. Since there is no transmit antenna at $D$ initially, all transmit power should be allocated to the source, i.e., $\alpha = 1$. Calculate the initial optimization objective as $\Lambda_{\mathbb{A}_T}^{max}$. At each iteration, one receive antenna $a_n$ in $\mathbb{A}_R$ is selected arbitrarily and switched to work in the transmit mode, and we mark $\mathbb{A}_T = \mathbb{A}_T \cup [a_n]$, thus there exists $card(\mathbb{A}_R)$ ways of choosing $a_n$. Then the OPA factor $\alpha_{\mathbb{A}_T}^* \in \left\{\alpha_{\mathbb{A}_T}^{I*}, \alpha_{\mathbb{A}_T}^{S*}\right\}$ and $\Lambda_{\mathbb{A}_T}$ for every feasible antenna set are calculated. The maximal value of optimization objective $\Lambda_{\mathbb{A}_T}^{max}$ and the corresponding $\mathbb{A}_T$ are obtained accordingly. The core of this proposed AMS-OPA scheme is to evaluate whether there is a performance gain for $\Lambda_{\mathbb{A}_T}$ when one receive antenna in $\mathbb{A}_R$ is switched to the transmit mode. The algorithm terminates till there is a single antenna left in $\mathbb{A}_R$, and outputs the optimal solutions, i.e., $\mathbb{A}_T^{opt}$, $\mathbb{A}_R^{opt}$, $\alpha_{\mathbb{A}_T^{opt}}^*$ and $\Lambda_{\mathbb{A}_T^{opt}}$.

**Algorithm 1** Proposed AMS-OPA Scheme

INITIALIZATION: Set the initial optimal transmit antenna set $\mathbb{A}_T^{opt} = \emptyset$ and $\alpha = 1$. Calculate the initial maximal optimization objective for $card(\mathbb{A}_T) = 0$ as $\Lambda_{\mathbb{A}_T^{opt}}$;
FOR $i = 1 : N_D - 1$
1: For each available mode-to-switch antenna $a_n$ in $\mathbb{A}_R$, set a feasible transmit antenna set as $\mathbb{A}_T = \mathbb{A}_T \cup [a_n]$. Calculate $\alpha_{\mathbb{A}_T}^*$ and $\Lambda_{\mathbb{A}_T}$;
2: Obtain the maximal value $\Lambda_{\mathbb{A}_T}^{max}$ based on (27) among all possible values obtained from the above step, and determine the corresponding local optimal $\mathbb{A}_T$, i.e., $\mathbb{A}_T^{loc}$;
3: IF $\Lambda_{\mathbb{A}_T}^{max} \ge \Lambda_{\mathbb{A}_T^{opt}}$
  $\mathbb{A}_T^{opt} = \mathbb{A}_T^{loc}$;
  $\mathbb{A}_T = \mathbb{A}_T^{loc}$;
 ELSE
  $\mathbb{A}_T = \mathbb{A}_T^{loc}$;
 END IF
END FOR
OUTPUT: $\mathbb{A}_T^{opt}$, $\mathbb{A}_R^{opt}$, $\alpha_{\mathbb{A}_T^{opt}}^*$ and $\Lambda_{\mathbb{A}_T^{opt}}$;

$$R_S^S = \begin{cases} \log_2\left[\dfrac{\left(1+\alpha P\gamma_{SD}^{\mathbb{A}_R}\right)(1-\alpha)(N_{Dt}-1)\Omega_{DE}}{(1-\alpha)(N_{Dt}-1)\Omega_{DE}+\alpha\Omega_{SE}N_{Dt}}\right], & 0 \le \alpha \le 1-\dfrac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)P\Omega_{DE}\gamma_{SD}^{\mathbb{A}_R}} \\ 0, & 1-\dfrac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)P\Omega_{DE}\gamma_{SD}^{\mathbb{A}_R}} < \alpha \le 1 \end{cases} \quad (24)$$

### E. COMPLEXITY ANALYSIS

In the following, we will compare the search complexity of exhaustive searching AMS (ES-AMS-OPA) scheme and the proposed AMS-OPA scheme.

*Proposition 1:* The ES-AMS-OPA scheme for finding the optimal antenna set $\mathbb{A}_T^{opt}$ can be classified as a Non-deterministic Polynomial-time (NP)-hard problem, because the search complexity of the ES-AMS-OPA scheme is $O\left(2^{N_D}\right)$.

*Proof:* The total number of feasible antenna sets for the ES-AMS-OPA scheme is calculated as

$$\mathcal{C}_{es} = \sum_{N_{Dt}=0}^{N_D-1} \binom{N_D}{N_{Dt}} = 2^{N_D} - 1. \tag{28}$$

Thus, the search complexity of ES-AMS-OPA is $O\left(2^{N_D}\right)$. ■

*Proposition 2:* The search complexity of the proposed AMS-OPA scheme is $O\left(N_D^2\right)$, and the proposed algorithm can converge.

*Proof:* The proposed AMS-OPA scheme is a greedy algorithm based procedure. Thus, the number of mode-to-switch antennas in set $\mathbb{A}_R$ decreases as $N_{Dt}$ increases every single time. Thus, the total number of feasible antenna sets for all possible $N_{Dt}$ is much smaller compared with that of the ES-AMS-OPA scheme. The total number of feasible antenna sets for the proposed AMS-OPA scheme is derived as

$$\mathcal{C}_{ps} = \sum_{N_{Dt}=1}^{N_D-1} \binom{N_D - N_{Dt} + 1}{1} + 1 = \frac{N_D^2}{2} + \frac{N_D}{2}. \tag{29}$$

Therefore, the search complexity of the proposed AMS-OPA scheme is $O\left(N_D^2\right)$. In (29), the term $\binom{N_D-N_{Dt}+1}{1}$ illustrates the fact that, at each iteration of the proposed MS-OPA scheme, only one additional antenna will be selected from the latest receive antenna set $\mathbb{A}_R$.

Since the proposed AMS-OPA method is designed to find the optimal solutions by means of comparing the optimization objective among all possible antenna sets, and the number of feasible antenna sets is finite, it can converge. ■

From *Proposition 1* and *Proposition 2*, we can see that the search complexity of ES-AMS-OPA method increases exponentially as $N_D$ grows, and the complexity becomes prohibitive in practice. Compared with ES-AMS-OPA method, the proposed AMS-OPA scheme has much lower search complexity and is time efficient, especially when $N_D$ is large. Table 1 shows the search complexity comparison between the ES-AMS-OPA scheme and the proposed AMS-OPA scheme.

**TABLE 1. Comparison of search complexity.**

| | ES-AMS-OPA | Proposed AMS-OPA |
|---|---|---|
| Search complexity | $O\left(2^{N_D}\right)$ | $O\left(N_D^2\right)$ |

### F. PERFORMANCE ANALYSIS OF THE PROPOSED AMS-OPA SCHEME

The proposed AMS-OPA scheme is a sub-optimal but low-complexity method to maximize the achievable secrecy rate for the system. The performance gap between the optimal ES-AMS-OPA method and the proposed sub-optimal AMS-OPA scheme is caused by that the total numbers of the feasible transmit and receive antenna sets for the two schemes are not the same. The ES-AMS-OPA is the optimal method to achieve the maximal achievable secrecy rate, because it can traverse all possible feasible antenna sets and pick the optimal antenna sets among them. However, the proposed AMS-OPA scheme can only traverse a part of all possible feasible antenna sets, that directly causes the performance gap between the two schemes. According to complexity analysis, with the increase of $N_D$, the difference between the total numbers of feasible antenna sets for the two schemes, i.e., $O\left(2^{N_D}\right) - O\left(N_D^2\right)$ is getting larger, resulting in a larger performance gap, which will be verified in the numerical results of this paper. For all $N_D$ regime, the proposed AMS-OPA scheme can theoretically achieve sub-optimal achievable secrecy rate performance for the system with a

$$\alpha_{\mathbb{A}_T}^{S*} = \begin{cases} \begin{cases} \dfrac{\gamma_{SD}^{\mathbb{A}_R}\left(N_{Dt}-1\right)\Omega_{DE}P - \Upsilon}{\gamma_{SD}^{\mathbb{A}_R}P\left[\left(N_{Dt}-1\right)\Omega_{DE} - N_{Dt}\Omega_{SE}\right]}, & \gamma_{SD}^{\mathbb{A}_R} > \dfrac{N_{Dt}\Omega_{SE}}{\left(N_{Dt}-1\right)P\Omega_{DE}} \&\& \left(N_{Dt}-1\right)\Omega_{DE} - N_{Dt}\Omega_{SE} \neq 0 \\ \dfrac{1}{2}\left(1 - \dfrac{1}{\gamma_{SD}^{\mathbb{A}_R}P}\right), & \gamma_{SD}^{\mathbb{A}_R} > \dfrac{N_{Dt}\Omega_{SE}}{\left(N_{Dt}-1\right)P\Omega_{DE}} \&\& \left(N_{Dt}-1\right)\Omega_{DE} - N_{Dt}\Omega_{SE} = 0 \\ NO\ OPA\ factor, & \gamma_{SD}^{\mathbb{A}_R} \leq \dfrac{N_{Dt}\Omega_{SE}}{\left(N_{Dt}-1\right)P\Omega_{DE}} \end{cases}, & N_{Dt} \geq 2 \\ \begin{cases} \dfrac{\gamma_{SD}^{\mathbb{A}_R}\Omega_{DE}P - \Delta}{\gamma_{SD}^{\mathbb{A}_R}P\left[\Omega_{DE} - \Omega_{SE}\right]}, & \gamma_{SD}^{\mathbb{A}_R} > \dfrac{\Omega_{SE}}{P\Omega_{DE}} \&\& \Omega_{DE} - \Omega_{SE} \neq 0 \\ \dfrac{1}{2}\left(1 - \dfrac{1}{\gamma_{SD}^{\mathbb{A}_R}P}\right), & \gamma_{SD}^{\mathbb{A}_R} > \dfrac{\Omega_{SE}}{P\Omega_{DE}} \&\& \Omega_{DE} - \Omega_{SE} = 0 \\ NO\ OPA\ factor, & \gamma_{SD}^{\mathbb{A}_R} \leq \dfrac{\Omega_{SE}}{P\Omega_{DE}} \end{cases}, & N_{Dt} = 1 \end{cases} \tag{26}$$

much lower complexity and is a trade-off between complexity and performance.

## IV. NUMERICAL RESULTS

In this section, numerical results are provided to evaluate the performance of the proposed joint optimization scheme of AMS and OPA in FD-DBJ secure transmission system. In order to show stable, reliable and reproducible simulation results, all figures shown in this section are generated by Monte Carlo method, and the average values are obtained by $10^6$ random channel realizations. We assume the average channel power gains as $\Omega_{SD} = \Omega_{SE} = \Omega_{DE} = 1$ for all figures. For the purpose of comparison, we also simulate the performance of the conventional FD-DBJ scheme, which represents that $D$ applies the DBJ using fixed-mode transmit and receive antennas and the number of transmit antennas is equal to that of receive antennas.

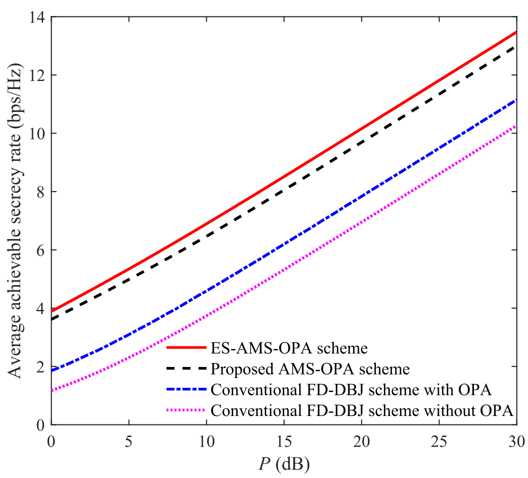


**FIGURE 2. Average achievable secrecy rate in instantaneous ECSIs case versus total transmit power, $N_D = 10$, $\Omega_{SD} = \Omega_{SE} = \Omega_{DE} = 1$.**

In Fig. 2, the average achievable secrecy rate performance in instantaneous ECSIs case for different transmission strategies is evaluated. We assume $N_D = 10$ for all schemes, and $N_{Dt} = N_{Dr} = 5$ for two conventional FD-DBJ schemes. The PA factor is set as $\alpha = 0.3$ for the conventional FD-DBJ scheme without OPA, and set as (17) for that with OPA. From Fig. 2, we can find that the ES-AMS-OPA scheme has the best performance, and can be regarded as a benchmark which is the theory limit for the average achievable secrecy rate performance of the system. However, the search complexity of ES-AMS-OPA scheme is too high to achieve the expected performance in practice as $N_D$ is relatively large. The performance of the proposed AMS-OPA scheme is very close to that of ES-AMS-OPA method, with a much lower search complexity. Moreover, both proposed AMS-OPA and ES-AMS-OPA schemes are substantially superior to two conventional FD-DBJ schemes, showing the advantage of AMS. Furthermore, the conventional FD-DBJ scheme without OPA performs worse than that with OPA, revealing the important role of the OPA technique on the performance improvement.

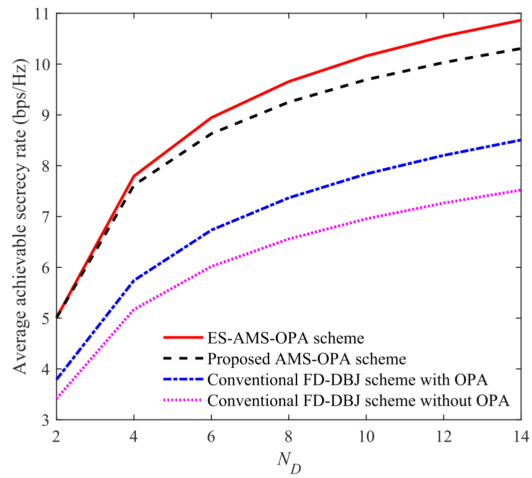


**FIGURE 3. Average achievable secrecy rate in instantaneous ECSIs case versus $N_D$, $P = 20$dB, $\Omega_{SD} = \Omega_{SE} = \Omega_{DE} = 1$.**

The simulation results also reveal that both AMS and OPA techniques are indispensable to optimize the system performance of the proposed joint optimization scheme.

Fig. 3 indicates the average achievable secrecy rate of different schemes in instantaneous ECSIs case versus $N_D$ for $P = 20$dB. The PA factor configurations for two conventional FD-DBJ schemes is same as that described in Fig. 2. From Fig. 3, it is obvious that the performance of the proposed scheme is nearly optimal compared with ES-AMS-OPA for small $N_D$, e.g., $N_D \leq 4$. With the increase of $N_D$, the performance of the proposed scheme can still approach that of the optimal scheme with much lower complexity, although the gap between them gradually increases. It is also observed that, the proposed scheme outperforms both the conventional FD-DBJ schemes with considerable secrecy rate gain for different values of $N_D$. Notably, the proposed scheme can provide evident performance gain even for small number of antennas.

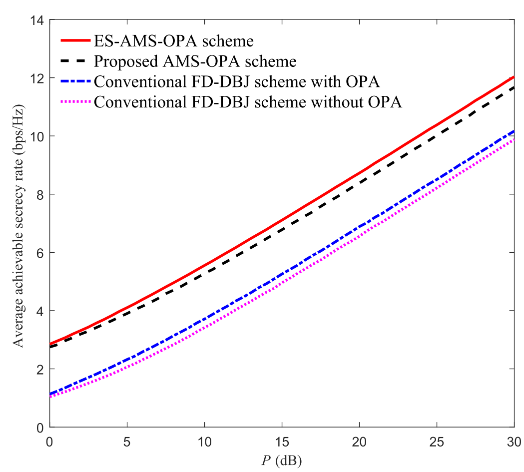


**FIGURE 4. Average achievable secrecy rate in statistical ECSIs case versus total transmit power, $N_D = 10$, $\Omega_{SD} = \Omega_{SE} = \Omega_{DE} = 1$.**

In Fig. 4, the average achievable secrecy rate performance in statistical ECSIs case for different transmission strategies is evaluated. We assume $N_D = 10$ for all schemes, and

$N_{Dt} = N_{Dr} = 5$ for two conventional FD-DBJ schemes. The PA factor is set as $\alpha = 0.3$ for the conventional FD-DBJ scheme without OPA, and set as (26) for that with OPA. From Fig. 4, we can find that our proposed optimization scheme is valid even in circumstance that the legitimate nodes can only obtain the statistical ECSIs.

## V. CONCLUSIONS

A low-complexity near-optimal joint optimization scheme of AMS and OPA was proposed for the FD-DBJ secure transmission system in this paper. The proposed joint optimization scheme is valid for two different eavesdropping channel state information (ECSI) availability cases, i.e., instantaneous ECSIs and statistical ECSIs. To improve the secrecy performance of the FD-DBJ system with dynamic-mode antennas, we applied a two-step optimization approach. First, we derive the closed-form optimal power allocation factors for both ECSIs availabilities. Second, we design a greedy-search-based transmit and receive antennas assignment algorithm combining the OPA factor. Simulation results indicated that the system utilizing the proposed joint optimization scheme outperforms that applying the conventional fixed-mode antennas based method, and exhibits near-optimal average achievable secrecy rate performance with much lower complexity.

## APPENDIX

### A. PROOF OF THEOREM 1

In the instantaneous ECSIs circumstance, the second derivative of (8) is expressed as

$$\frac{\partial^2 \Lambda^I}{\partial \alpha^2} = \Theta \cdot \Gamma, \tag{30}$$

where

$$\Theta = \frac{2P^2\gamma_{SE}\left(1 + P\gamma_{DE}^{\mathbb{A}_T}\right)}{\left(1 + (1-\alpha)P\gamma_{DE}^{\mathbb{A}_T} + \alpha P\gamma_{SE}\right)^3}, \tag{31}$$

which is always positive, and $\Gamma = \gamma_{SE} - \left(\gamma_{DE}^{\mathbb{A}_T} + \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P\right)$. Hence the concavity of the function is only effected by $\Gamma$.

When $\Gamma > 0$, the expression (8) is strictly convex w.r.t. $\alpha$, and we have

$$\begin{aligned}\gamma_{SE} &> \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{DE}^{\mathbb{A}_T}\\ &> \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P.\end{aligned} \tag{32}$$

From *Lemma 1*, we know that the positive secrecy rate can not be achieved. Thus, the case of $\Gamma > 0$ can be ignored in the optimization process.

When $\Gamma \le 0$, the expression (8) is concave w.r.t. $\alpha$, and we have

$$\gamma_{SE} \le \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{DE}^{\mathbb{A}_T}. \tag{33}$$

Invoking *Lemma 1*, we find that, in the case of $\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R} \le \gamma_{SE} \le \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{DE}^{\mathbb{A}_T}$, the positive secrecy rate is not achievable, i.e., $R_S = 0$ with $0 \le \alpha \le 1$. Thus, the case $\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R} \le \gamma_{SE} \le \gamma_{SD}^{\mathbb{A}_R} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{DE}^{\mathbb{A}_T}$ can also be ignored in the optimization process.

As a result, when $\gamma_{SE} \ge \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P + \gamma_{SD}^{\mathbb{A}_R}$, $R_S = 0$ for $0 \le \alpha \le 1$. Thus, there is no OPA factor for $\alpha \in [0, 1]$ in this case.

In the case of $\gamma_{SE} \le \gamma_{SD}^{\mathbb{A}_R}$, the function (8) is a strictly concave function w.r.t. $\alpha$, and the feasible antenna sets for $\alpha$ are convex, the KKT conditions which are clearly defined in [37] are sufficient for achieving the optimal solution with the Lagrange function

$$L^I(\alpha, \mu) = \Lambda^I - \mu(\alpha - 1), \tag{34}$$

where $\mu \ge 0$ is the Lagrange multiplier associated with the constraint $\alpha - 1 \le 0$. The KKT conditions are stated by

$$\frac{\partial L^I(\alpha,\mu)}{\partial \alpha} = \frac{\partial \Lambda^I}{\partial \alpha} - \mu = 0, \tag{35}$$

$$\mu(\alpha - 1) = 0, \tag{36}$$

$$\alpha - 1 \le 0. \tag{37}$$

In (35), $\frac{\partial \Lambda^I}{\partial \alpha}$ is given by

$$\frac{\partial \Lambda^I}{\partial \alpha} = \frac{P\Phi}{\left[1 + (1-\alpha)P\gamma_{DE}^{\mathbb{A}_T} + \alpha P\gamma_{SE}\right]^2}, \tag{38}$$

where

$$\begin{aligned}\Phi = &-\gamma_{SE}\left(1 + P\gamma_{DE}^{\mathbb{A}_T}\right) + \gamma_{SD}^{\mathbb{A}_R}\Big[1 + (1-\alpha)^2\\ &\times P^2\gamma_{DE}^{\mathbb{A}_T 2} + 2P\gamma_{DE}^{\mathbb{A}_T} - \alpha P\gamma_{DE}^{\mathbb{A}_T}(2 + \alpha P\gamma_{SE})\Big].\end{aligned} \tag{39}$$

There are two groups of solutions for the KKT conditions. First, $\alpha_1 = 1$, and $\mu = \frac{\partial \Lambda^I}{\partial \alpha}|_{\alpha=1}$. Second, $0 < \alpha < 1$, and $\mu = 0$. When $\mu = 0$, and $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} \ne 0$, by solving $\frac{\partial \Lambda^I}{\partial \alpha} = 0$, we have two roots as

$$\alpha_2 = \frac{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P\left(1 + P\gamma_{DE}^{\mathbb{A}_T}\right) + \Psi}{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P^2\left(\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}\right)}, \tag{40}$$

$$\alpha_3 = \frac{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P\left(1 + P\gamma_{DE}^{\mathbb{A}_T}\right) - \Psi}{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P^2\left(\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}\right)}, \tag{41}$$

whose values depend on $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}$, where

$$\begin{aligned}\Psi = &\sqrt{\gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}\gamma_{SE}P^2\left(1 + \gamma_{DE}^{\mathbb{A}_T}P\right)}\\ &\times\sqrt{\gamma_{DE}^{\mathbb{A}_T} + \gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE} + \gamma_{SD}^{\mathbb{A}_R}\gamma_{DE}^{\mathbb{A}_T}P}.\end{aligned} \tag{42}$$

In the case of $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} > 0$, the first part and the second part of $\alpha_2$ are all positive, the first part can be expressed as

$$\frac{1 + \frac{1}{\gamma_{DE}^{\mathbb{A}_T}P}}{1 - \frac{\gamma_{SE}}{\gamma_{DE}^{\mathbb{A}_T}}} > 1, \tag{43}$$

hence, $\alpha_2 > 1$.

In the case of $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} < 0$, it is easy to find out that $\alpha_2 < 0$. In conclusion, $\alpha_2$ is not feasible.

Furthermore, the OPA factor $\alpha$ is determined through monotonicity analysis of (8), which is based on the first-order derivative (38).

In the case of $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} \neq 0$, (38) can be formulated as

$$\frac{\partial \Lambda^I}{\partial \alpha} = \left(\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}\right)(\alpha - \alpha_2)(\alpha - \alpha_3) \times \frac{P^3 \gamma_{SD}^{\mathbb{A}_R} \gamma_{DE}^{\mathbb{A}_T}}{\left[1 + (1-\alpha) P \gamma_{DE}^{\mathbb{A}_T} + \alpha P \gamma_{SE}\right]^2}. \quad (44)$$

Whether the above expression is positive or negative depends only on $\left(\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}\right)(\alpha - \alpha_2)(\alpha - \alpha_3)$.

When $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} > 0$, we get $\alpha_2 > 1$, so $\left(\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}\right)(\alpha - \alpha_2) < 0$. And when $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} < 0$, we have $\alpha_2 < 0$, so $\left(\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE}\right)(\alpha - \alpha_2) < 0$. From the above analysis, in the case of $\alpha_3 \geq 1$, $\frac{\partial \Lambda^I}{\partial \alpha}$ is non-negative among $\alpha \in (0, 1]$, so the optimal value is $\alpha^* = 1$, in the case of $\alpha_3 < 1$, $\frac{\partial \Lambda^I}{\partial \alpha}$ is non-negative among $\alpha \in (0, \alpha_3]$, and is negative among $(\alpha_3, 1]$, i.e., $\alpha^* = \alpha_3$. Hence, $\alpha^* = \min(\alpha_3, 1)$.

When $\mu = 0$ and $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} = 0$, it is derived from $\frac{\partial \Lambda^I}{\partial \alpha} = 0$ that

$$\alpha_4 = \frac{\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE} + \gamma_{SD}^{\mathbb{A}_R} \gamma_{SE} P}{2\gamma_{SD}^{\mathbb{A}_R} \gamma_{SE} P} = \frac{1}{2} + \frac{\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}}{2\gamma_{SD}^{\mathbb{A}_R} \gamma_{SE} P} \geq \frac{1}{2}. \quad (45)$$

Furthermore, (38) can be formulated as

$$\frac{\partial \Lambda^I}{\partial \alpha} = -\frac{2\gamma_{SD}^{\mathbb{A}_R} \gamma_{SE} P^2}{1 + \gamma_{SE} P}(\alpha - \alpha_4). \quad (46)$$

When $\alpha_4 > 1$, thus $\alpha - \alpha_4 < 0$, we can know $\frac{\partial \Lambda^I}{\partial \alpha} > 0$ among $\alpha \in (0, 1]$, so the optimal value is $\alpha^* = 1$. When $\alpha_4 \leq 1$, $\frac{\partial \Lambda^I}{\partial \alpha}$ is non-negative among $\alpha \in (0, \alpha_4]$, and is negative among $(\alpha_4, 1]$, i.e., $\alpha^* = \alpha_4$. In conclusion, $\alpha^* = \min(\alpha_4, 1)$.

In the case of $\gamma_{SD}^{\mathbb{A}_R} < \gamma_{SE} < \gamma_{SD}^{\mathbb{A}_R} \gamma_{DE}^{\mathbb{A}_T} P + \gamma_{SD}^{\mathbb{A}_R}$, the function is a strict concave function with $0 \leq \alpha \leq 1 + \left(\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}\right) / \left(P\gamma_{SD}^{\mathbb{A}_R} \gamma_{DE}^{\mathbb{A}_T}\right)$. It is easy to know that $\alpha = 0$ or $\alpha = 1 + \left(\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}\right) / \left(P\gamma_{SD}^{\mathbb{A}_R} \gamma_{DE}^{\mathbb{A}_T}\right)$, we know that $\Lambda^I = 1$. Thus, the only OPA factor must be located at the place which satisfies $\frac{\partial \Lambda^I}{\partial \alpha} = 0$ among $\alpha \in (0, 1 + \left(\gamma_{SD}^{\mathbb{A}_R} - \gamma_{SE}\right) / \left(P\gamma_{SD}^{\mathbb{A}_R} \gamma_{DE}^{\mathbb{A}_T}\right))$. From the above analysis, we know that, in the case of $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} \neq 0$, $\alpha^* = \alpha_3$, and in the case of $\gamma_{DE}^{\mathbb{A}_T} - \gamma_{SE} = 0$, $\alpha^* = \alpha_4$.

Finally, under the condition of instantaneous ECSIs, the OPA factor can be formulated as (17).

### B. PROOF OF THEOREM 2

In the situation of statistical ECSIs and under the condition of $N_{Dt} \geq 2$, the second derivative of (22) is expressed as

$$\frac{\partial^2 \Lambda^S}{\partial \alpha^2} = \omega \cdot \varepsilon, \quad (47)$$

where

$$\omega = \frac{2(N_{Dt} - 1) N_{Dt} \Omega_{SE} \Omega_{DE}}{\left[(1-\alpha)(N_{Dt} - 1)\Omega_{DE} + \alpha N_{Dt} \Omega_{SE}\right]^3}, \quad (48)$$

which is always positive, and $\varepsilon = N_{Dt}\Omega_{SE} - (N_{Dt} - 1)\Omega_{DE}\left(1 + \gamma_{SD}^{\mathbb{A}_R} P\right)$. Therefore, $\varepsilon$ is the only factor that can affect the concavity of $\Lambda^S$ in the case of $N_{Dt} \geq 2$.

When $\varepsilon > 0$ and $N_{Dt} \geq 2$, the function $\Lambda^S$ is strictly convex w.r.t. $\alpha$, and we obtain

$$\gamma_{SD}^{\mathbb{A}_R} < \frac{N_{Dt}\Omega_{SE}}{(N_{Dt} - 1)\Omega_{DE} P} - \frac{1}{P} < \frac{N_{Dt}\Omega_{SE}}{(N_{Dt} - 1)\Omega_{DE} P}. \quad (49)$$

From *Lemma 2*, we know that the positive secrecy rate can not be achieved for $\alpha \in [0, 1]$. Thus, the case of $\varepsilon > 0$ can be ignored in the optimization process.

When $\varepsilon \leq 0$ and $N_{Dt} \geq 2$,the function $\Lambda^S$ is concave w.r.t. $\alpha$, and we get

$$\gamma_{SD}^{\mathbb{A}_R} \geq \frac{N_{Dt}\Omega_{SE}}{(N_{Dt} - 1)\Omega_{DE} P} - \frac{1}{P}. \quad (50)$$

From *Lemma2*, we can find that, in the circumstance of $\frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)\Omega_{DE} P} - \frac{1}{P} \leq \gamma_{SD}^{\mathbb{A}_R} \leq \frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)\Omega_{DE} P}$, the positive secrecy rate is not achievable for $\alpha \in [0, 1]$. Therefore, we do not consider this situation in the optimization process.

In the case of $\gamma_{SD}^{\mathbb{A}_R} \geq \frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)\Omega_{DE} P}$ and $N_{Dt} \geq 2$, the function $\Lambda^S$ is strictly concave w.r.t. $\alpha$, and the feasible antenna sets for $\alpha$ are convex, the KKT conditions are sufficient to find all possible OPA factors with the Lagrange function

$$L^S(\alpha, \mu) = \Lambda^S - \mu(\alpha - 1). \quad (51)$$

The KKT conditions can be stated as

$$\frac{\partial L^S(\alpha, \mu)}{\partial \alpha} = \frac{\partial \Lambda^S}{\partial \alpha} - \mu = 0, \quad (52)$$

$$\mu(\alpha - 1) = 0, \quad (53)$$

$$\alpha - 1 \leq 0. \quad (54)$$

In (52), $\frac{\partial \Lambda^S}{\partial \alpha}$ is written as

$$\frac{\partial \Lambda^S}{\partial \alpha} = \frac{(N_{Dt} - 1)\Omega_{DE}\Xi}{\left[(1-\alpha)(N_{Dt} - 1)\Omega_{DE} + \alpha N_{Dt}\Omega_{SE}\right]^2}, \quad (55)$$

where

$$\Xi = (N_{Dt} - 1)(1-\alpha)^2 \gamma_{SD}^{\mathbb{A}_R} \Omega_{DE} P - N_{Dt}\Omega_{SE}\left(1 + \alpha^2 \gamma_{SD}^{\mathbb{A}_R} P\right). \quad (56)$$

There are two groups of solutions for the KKT conditions. First, $\alpha_1 = 1$, and $\mu = \frac{\partial \Lambda^S}{\partial \alpha}|_{\alpha=1}$. Second, $0 < \alpha < 1$, and $\mu = 0$. When $\mu = 0$, and $(N_{Dt} - 1)\,\Omega_{DE} - N_{Dt}\Omega_{SE} \neq 0$, by solving $\frac{\partial \Lambda^S}{\partial \alpha} = 0$, we have two roots as

$$\alpha_2 = \frac{\gamma_{SD}^{\mathbb{A}_R}(N_{Dt}-1)\,\Omega_{DE}P + Y}{\gamma_{SD}^{\mathbb{A}_R}P\left[(N_{Dt}-1)\,\Omega_{DE} - N_{Dt}\Omega_{SE}\right]}, \tag{57}$$

$$\alpha_3 = \frac{\gamma_{SD}^{\mathbb{A}_R}(N_{Dt}-1)\,\Omega_{DE}P - Y}{\gamma_{SD}^{\mathbb{A}_R}P\left[(N_{Dt}-1)\,\Omega_{DE} - N_{Dt}\Omega_{SE}\right]}, \tag{58}$$

whose values depend on $(N_{Dt} - 1)\,\Omega_{DE} - N_{Dt}\Omega_{SE}$, where

$$Y = \sqrt{\gamma_{SD}^{\mathbb{A}_R}PN_{Dt}\Omega_{SE}} \times \sqrt{(N_{Dt}-1)\,\Omega_{DE}\left(1+\gamma_{SD}^{\mathbb{A}_R}P\right) - N_{Dt}\Omega_{SE}}. \tag{59}$$

When $(N_{Dt} - 1)\,\Omega_{DE} - N_{Dt}\Omega_{SE} > 0$, the first part and the second part of $\alpha_2$ are all positive, the first part can be expressed as

$$\frac{1}{1 - \frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)\Omega_{DE}}} > 1, \tag{60}$$

hence, $\alpha_2 > 1$.

In the case of $(N_{Dt} - 1)\,\Omega_{DE} - N_{Dt}\Omega_{SE} < 0$, it is easy to find out that $\alpha_2 < 0$. In conclusion, $\alpha_2$ is not feasible.

Invoking *Lemma 2* and in the case of $\gamma_{SD}^{\mathbb{A}_R} \geq \frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)\Omega_{DE}P}$, we know that $\Lambda^S$ is a strictly concave function w.r.t. $\alpha$ for $0 \leq \alpha \leq 1 - \frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)P\Omega_{DE}\gamma_{SD}^{\mathbb{A}_R}}$. Thus, there must exist a OPA factor between $0 \leq \alpha \leq 1 - \frac{N_{Dt}\Omega_{SE}}{(N_{Dt}-1)P\Omega_{DE}\gamma_{SD}^{\mathbb{A}_R}}$. From the above analysis, $\alpha_1$ or $\alpha_2$ is not the feasible one among all the three possible OPA factors. Therefore, $\alpha_3$ is the OPA factor we seek, i.e., $\alpha^* = \alpha_3$.

When $\mu = 0$ and $(N_{Dt} - 1)\,\Omega_{DE} - N_{Dt}\Omega_{SE} = 0$, it is derived from $\frac{\partial \Lambda^S}{\partial \alpha} = 0$ that the only root is as

$$\alpha_4 = \frac{1}{2}\left(1 - \frac{1}{\gamma_{SD}^{\mathbb{A}_R}P}\right). \tag{61}$$

For the same reason as $\alpha^* = \alpha_3$, in the case of $\mu = 0$ and $(N_{Dt} - 1)\,\Omega_{DE} - N_{Dt}\Omega_{SE} = 0$, $\alpha^* = \alpha_4$. The derivation process of the OPA factor for $N_{Dt} \geq 2$ is completed.

We note that, in the case of $N_{Dt} = 1$, the derivation process of the OPA factor is similar as that for $N_{Dt} \geq 2$, we omit it for conciseness. In the case of $N_{Dt} = 0$, $\alpha$ is set to the constant 1, thus we treat $\alpha = 1$ as the OPA factor.

In the end, under the condition of statistical ECSIs, the OPA factor can be formulated as (26).

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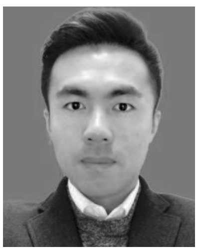

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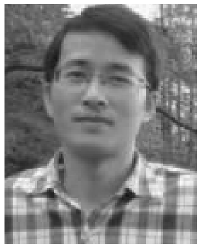

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