Secrecy Outage and Diversity Analysis of Multiple Cooperating Source-Destination Pairs

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***Abstract*—We study the physical-layer security of multiple source-destination (SD) pairs communicating within a wireless network in the face of an eavesdropper attacking the SD pairs. In order to protect the wireless transmission against eavesdropping, we propose a cooperation framework relying on two stages. Specifically, an SD pair is selected to access the total allocated spectrum using an appropriately designed scheme at the beginning of the first stage. The other source nodes (SNs) simultaneously transmit their data to the SN of the above-mentioned SD pair relying on orthogonal resources during the first stage. Then, the SN of the chosen SD pair transmits the data packets containing its own messages and the other SNs' messages to its dedicated destination node (DN) in the second stage. Finally, this dedicated DN will forward all the other DNs' data to the application center via the core network. We conceive a specific SD pair selection scheme, termed as the transmit antenna selection aided source-destination pair selection (TAS-SDPS). We continue by deriving the secrecy outage probability (SOP) expressions of both the TAS-SDPS conceived, as well as of the conventional round-robin source-destination pair selection (RSDPS) and of the conventional non-cooperative (Non-coop) schemes for comparison. Furthermore, we carry out the secrecy diversity gain analysis in the high main-to-eavesdropper ratio (MER) region, showing that the TAS-SDPS scheme is capable of achieving the maximum attainable secrecy diversity order. Additionally, we show that increasing the number of transmitting pairs will reduce the SOP, whilst increasing the secrecy diversity order of the TAS-SDPS scheme. It is demonstrated that the SOP of the TAS-SDPS scheme is better than that of the RSDPS and of the conventional Non-coop schemes. We also demonstrate that the secrecy diversity gain of the proposed TAS-SDPS scheme is M times that of the RSDPS scheme in the high-MER region, where M is the number of the SD pairs.**

***Index Terms*—Physical-layer security, source-destination pair selection, secrecy outage probability, secrecy diversity gain.**

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I. Introduction

Multiple source-destination pairs are capable of efficient simultaneously communications with the aid of dynamic spectrum-sharing techniques [1]-[5], whilst limiting the interference imposed on each other. However, multiple source-destination (SD) pairs coexisting in wireless systems may be vulnerable to both internal as well as to external attackers, when they operate independently in non-cooperative scenarios. For example, a hostile attacker may contaminate the legitimate transmission, thus degrading the quality of service (QoS). Furthermore, owing to the broadcast nature of radio propagation, the confidential messages may be overheard by malicious eavesdroppers, which has to be prevented.

Physical-layer security (PLS) [6]-[8] emerges as an effective method of guarding against wiretapping by exploiting the physical characteristics of wireless channels. Single-input multiple-output (SIMO) and multiple-input multiple-output (MIMO) schemes were conceived in [9], [10] for reducing the secrecy outage probability. Similarly, beamforming techniques were also invoked for improving the secrecy of wireless transmissions [11]-[12]. Moreover, the concept of cognitive jamming was explored in [13], while specially designed artificial noise was used for preventing eavesdropping in [14]. Furthermore, the authors of [15] and [16] explored opportunistic user scheduling conceived with cooperative jamming. More specifically, in [16], the non-scheduled users of the proposed user scheduling scheme were invoked for generating artificial noise in order to improve security in a multiuser wiretap network. Both one-way [17], [18] and two-way [19], [20] relaying schemes were conceived for guarding against eavesdropping, demonstrating that relay selection schemes are capable of improving the PLS. This is indeed expected, because they improve the quality of the desired link.

As a further development, PLS has also been designed for wireless networks supporting a multiplicity of diverse devices. The secrecy beamforming concept has been proposed by Lv et al. [21] for improving the PLS of heterogeneous networks. Moreover, jamming schemes have been investigated in [22]-[24]. To be specific, in [22], the jammers were selected to transmit jamming signals for contaminating the wiretapping reception of the eavesdroppers. Meanwhile, the interfering power imposed on the scheduled users was assumed to be below a threshold, and only the eavesdropper's channel was degraded. A comprehensive performance analysis of artificial-noise aided secure multi-antenna transmission relying on a stochastic geometry framework was provided in [23] for K-tier heterogeneous cellar networks. In [24], joint beamforming and artificial noise scheme were designed at the secondary transmitters to guarantee secure wireless transmission. In [25], antenna selection was used for improving the security of source-destination transmissions in a multi-antenna aided MIMO system consisting of one source, one destination and one eavesdropper. In [26], a novel transmission outage constrained scheme was proposed to degrade the transmission outage probabilities of the users, which was beneficial for decreasing the secrecy outage. Furthermore, the co-existence of a macro cell and a small cell constituting a simple cellular network was investigated by Zou [27]. Specifically, the overlay and underlay spectrum sharing schemes have been invoked for a macro cell and a small cell, respectively. Moreover, an interference-cancelation scheme was proposed for mitigating the interference in the underlay spectrum sharing case. In [28], Lei et al. explored the secrecy outage performance of an underlay MIMO cognitive radio network, and the optimal antenna selection and suboptimal antenna selection schemes were designed to reduce the secrecy outage of the wireless system investigated.

Against this backdrop, we explore the PLS of wireless networks supporting multiple SD pairs in the presence of an eavesdropper. In contrast to [21]-[28], we investigate the co-operation between different SD pairs for safeguarding against malicious eavesdropping with the aid of our specifically designed cooperative framework. In Table I we contrast the novelty of this paper to the most pertinent literature [21]-[28]. Moreover, we propose a pair of cooperation schemes based on SD pair scheduling. ***More explicitly, against this background, the main contributions of this paper are summarized as follows.***

1) Firstly, we propose a cooperative framework relying on two stages for protecting wireless transmissions against eavesdropping. Specifically, in the first stage, an SD pair will be chosen at the beginning of the transmission slot. Then, the other source nodes (SNs) will confidentially transmit their data to the chosen SN via orthogonal resources. In the second stage, the specifically chosen SN simultaneously transmits both its own data as well as that received from the other SNs to its destination node (DN), which will forward the received messages to the application center of the other SNs via the core network.
2) Secondly, we present a specific transmission selection scheme, termed as transmit antenna selection aided source-destination pair selection (TAS-SDPS). To be specific, in the TAS-SDPS scheme, the “best” antenna of a chosen SD pair will be selected for simultaneously transmitting both its own data and other SNs’ data relying on the total shared spectrum.
3) Thirdly, we analyze the secrecy outage probability (SOP) of the proposed TAS-SDPS scheme for transmission between SD pair over Rayleigh fading channels, whilst between the SNs Rician fading channels are assumed. We also evaluate the SOP of the traditional non-cooperative (Non-coop) and of the round-robin source-destination pair selection (RSDPS) for comparison. Moreover, we evaluate the secrecy diversity gains of both the TAS-SDPS and of the RSDPS schemes, demonstrating that the TAS-SDPS scheme is indeed capable of achieving the maximum attainable secrecy diversity gain.
4) Finally, it is shown that the SOP of the TAS-SDPS scheme will be beneficially reduced by increasing the number of SD pairs. Furthermore, the TAS-SDPS scheme outperforms both the RSDPS and the Non-coop schemes in terms of both the SOP and the secrecy diversity gain attained, demonstrating that the advantages of the proposed cooperative framework in terms of improving the security of wireless communications.

TABLE I
COMPARISONS BETWEEN OUR WORK AND THE RELATED [21]-[28].

	Our	[21]	[22]	[23]	[24]	[25]	[26]	[27]	[28]
Cooperative framework	✓								
BS with multiple antennas	✓	✓	✓	✓		✓			✓
User with multiple antennas	✓				✓	✓			✓
TAS-SDPS scheme	✓								
Secrecy outage probability	✓		✓		✓		✓		✓
Secrecy diversity gain	✓					✓	✓	✓	✓
Jamming			✓	✓	✓		✓	✓	
Secrecy rate		✓			✓				
Zero secrecy capacity						✓		✓	
Connection probability and secrecy probability				✓					
Against eavesdropping	✓	✓	✓	✓	✓	✓	✓	✓	✓

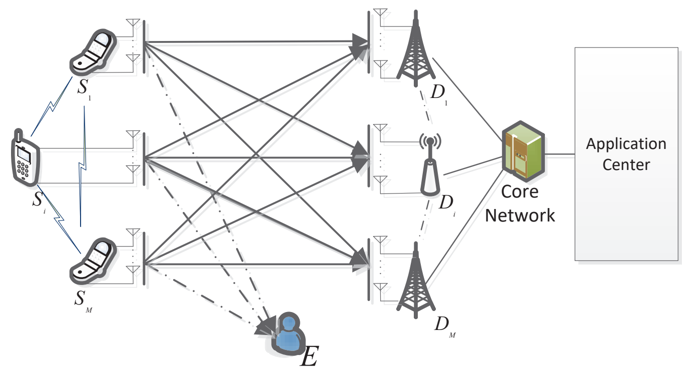

Fig. 1. A multiple SD pairs coexisting wireless network in the presence of an eavesdropper E.

The organization of this paper is as follows. In Section II, we briefly characterize the PLS of a multiple SD pairs coexisting wireless network. In Section III, we carry out the SOP analysis of the Non-coop, RSDPS, and TAS-SDPS schemes. In Section IV we evaluate the secrecy diversity gain of the proposed RSDPS and TAS-SDPS schemes. Our performance evaluations are detailed in Section V. Finally, in Section VI we conclude the paper.

II. System Model and SD Pairs Scheduling

A. System Model

As shown in Fig. 1, we consider M source-destination (SD) pairs in the presence of an eavesdropper (E), where the E intends to wiretap the wireless transmissions of the legitimate source nodes (SNs) with the aid of a wide-band receiver. Each SN is assumed to be equipped with two radio frequency (RF) units, one[1] of which is used for transmissions between the SNs, and the other one[2] is invoked for communicating with the destination node (DN). For notational convenience, we let $\mathbb{D}$ represent the set of the SD pairs. Moreover, both the SNs-DNs and SNs-E links are modeled by Rayleigh fading [19], and considering the mth SD pair, we assume that the SN m (S_m) is using the ith antenna, DN m (D_m) is employing the jth antenna, and the E is using the lth antenna. Then the channel gains of S_m-D_m and S_m-E, are denoted by $h_{s_{m_i}d_{m_j}}$, and $h_{s_{m_i}e_l}$, $m \in \{1, \cdots, M\}$, $i \in \{1, \cdots, N_T\}$, $j \in \{1, \cdots, N_R\}$, $l \in \{1, \cdots, N_E\}$, respectively, where N_T, N_R, and N_E denote the number of antennas of the S_m, the D_m, and the E, respectively. The expected values of $|h_{s_{m_i}d_{m_j}}|^2$, $|h_{s_{m_i}e_l}|^2$ and $|h_{s_k e_l}|^2$ are $\sigma^2_{s_{m_i}d_{m_j}}$, $\sigma^2_{s_{m_i}e_l}$, and $\sigma^2_{s_k e_l}$, respectively. For notational convenience, upon denoting $\sigma^2_{s_{m_i}d_{m_j}} = \alpha_{s_{m_i}d_{m_j}}\sigma^2_{md}$, $\sigma^2_{s_{m_i}e_l} = \alpha_{s_{m_i}e_l}\sigma^2_{me}$, and $\sigma^2_{s_k e_l} = \alpha_{s_k e_l}\sigma^2_{me}$, where σ^2_{md} and σ^2_{me} are the respective reference channel gain of the SNs-DNs links and SNs-E links. Furthermore, we assume that all SNs are located in each others' vicinity and the links between SNs are characterized by Rician fading [33], which are represented by $(h_{s_k s_m}, K_{s_k s_m})$, where $h_{s_k s_m}$ and $K_{s_k s_m}$ are the instantaneous channel gain of S_k-S_m link and the Rician K-factor of the S_k-S_m link, $m, k \in \{1, \cdots, M\}, k \neq m$. Additionally, we assume that each SD pair can access its own B Hz-sliver of bandwidth.

Our cooperative framework relies on two stages. To be specific, at the beginning of the first stage, an SN will be chosen according to the specific requirement of the proposed TAS-SDPS scheme, as detailed later. Then, the other SNs will simultaneously transmit their data to the appropriately selected SN using orthogonal resources (e.g., time-division, frequency-division, etc.). Moreover, in the second stage, the chosen SN will retransmit its own data and other SNs' data to its corresponding DN relying on orthogonal resources, where the DN will forward the received data to the application center through the core network.

B. Signal Model

In the first stage, let us assume that the SN S_m is selected as the forwarding node. Then, other SNs will transmit their signals to S_m on an orthogonal way with the aid of a single antenna, and S_m receives all the rest SNs's data simultaneously. Without loss of generality, the signal received at S_m transmitted by S_k, $k \in \mathbb{D} - \{m\}$, is given by:

$$y_{s_k s_m} = \sqrt{P_s} h_{s_k s_m} x_k + n_{s_m}, \tag{1}$$

where P_s, x_k, and n_{s_m} denotes the transmitted power of S_k, the transmitted signal of S_k, and the thermal noise received at the S_m, respectively. Without loss of generality, we assume that $E[|x_k|^2] = 1$, where $E[\cdot]$ denotes the operator of mathematical expectation. In the meantime, the signal transmitted by S_k will be overheard by E, which can be expressed as

$$y_{s_k e} = \sum_{l=1}^{N_E} \sqrt{P_s} h_{s_k e_l} x_k + n_e, \tag{2}$$

where n_e represents the thermal noise received at the E.

From (1) and (2), the achievable rate of the S_k-S_m and S_k-E links can be expressed as

$$C_{s_k s_m} = \frac{B}{2}\log_2(1 + \gamma_{s_k s_m}) \tag{3}$$

and

$$C_{s_k e} = \frac{B}{2}\log_2\left(1 + \gamma_{s_k e}\right), \tag{4}$$

respectively, where $\gamma_{s_k s_m} = \frac{P_s}{N_0}|h_{s_k s_m}|^2$, $\gamma_{s_k e} = \sum\limits_{l=1}^{N_E} \frac{P_s |h_{s_k e_l}|^2}{N_0}$, N_0 denotes the variance of the thermal noise of S_m, D_m, and E, respectively.

In the second stage, S_m transmits the successfully decoded data and its own data with the aid of orthogonal resources. Without loss of generality, we assume that the ith antenna of SN m (S_{m_i}) is chosen to transmit. Thus, the signal of an SN received at D_m from S_m can be formulated as

$$y_{s_{m_i} d_m} = \sum_{j=1}^{N_R} \sqrt{P_t} h_{s_{m_i} d_{m_j}} x_k + n_{d_m}, \tag{5}$$

where P_t and n_{d_m} denote the transmitted power of the ith antenna of S_m, and the thermal noise received at the D_m, respectively. Similarly to (3), the signal transmitted by S_m will be overheard by E, which can be written as

$$y_{s_{m_i} e} = \sum_{l=1}^{N_E} \sqrt{P_t} h_{s_{m_i} e_l} x_k + n_e. \tag{6}$$

Utilizing maximal-ratio combining (MRC) [37], for each SN, the achievable rate of the S_{m_i}-D_m links can be formulated as

$$C_{s_{m_i} d_m} = \frac{B}{2}\log_2\left(1 + \gamma_{s_{m_i} d_m}\right), \tag{7}$$

where we have $\gamma_{s_{m_i} d_m} = \sum\limits_{j=1}^{N_R} \frac{P_t |h_{s_{m_i} d_{m_j}}|^2}{N_0}$. Here we assume that all SNs have sufficient data to be transmitted, and they usually transmit their respective data of the same length in the given transmission slot. Additionally, if the different SNs's data lengths happen to be different, S_m may adjust each SN's data length to the same value, for example with the aid of data compression. Furthermore, the channel can be considered to be a flat-fading medium during the retransmission slot. Hence, the actually achievable rate for each SD pair is given by (7).

Using (6) and MRC, for each SN, the achievable rate of the S_m-E links can be expressed as

$$C_{s_m e} = \frac{B}{2}\log_2\left(1 + \gamma_{s_m e}\right), \tag{8}$$

[1]This RF unit can perform wireless transmissions with the aid of WiFi in the first stage. Specifically, this RF unit of the chosen SN can act as an access point (AP). By contrast, these RF units of other SNs operate in ordinary station mode, and the other SNs amy transmit their data to the chosen SN.

[2]Each SN may rely on any existing wireless technology (e.g 4G long term evolution (LTE)) for this RF unit during the second stage. Thus, the chosen SN may transmit its own data and that received from other SNs's data via different resource (e.g., time slots, sub-carriers, etc.).

where we have $\gamma_{s_m e} = \sum_{l=1}^{N_E} \frac{P_t |h_{s_{m_i} e_l}|^2}{N_0}$.

Using (4) and (8), the capacity achieved by E of S_k, $k \in \mathbb{D} - \{m\}$, can be obtained by using the maximum of the individual achievable rate of the S_m-E and S_k-E links in the first and second stages, i.e.

$$C_{se}^{(k,m)} = \max\left(C_{s_k e}, C_{s_m e}\right) = \frac{B}{2}\log_2\left[1 + \max\left(\gamma_{s_m e}, \gamma_{s_k e}\right)\right]. \tag{9}$$

As mentioned above, given the chosen transmission pair, the signal of the chosen SN will only be transmitted during the second stage. By contrast, the signal of other SNs will be transmitted both during the first stage and be forwarded in the second stage. Hence, the signal of the other SNs that are being overheard in the two stages has been given in (3) and (5), respectively. Noting that although only selection combining (SC) is considered, here similar results can be achieved with the aid of MRC. Moreover, as discussed in [17], when independent and different codewords are used in the two stages, MRC becomes inapplicable, whereas SC is still suitable for the E. Additionally, although in the two-step transmission the channel capacity of the wiretap channel (spanning from the source to the eavesdropper) may be higher than that of Non-coop transmission, the secrecy capacity can still be improved. This is due to the fact that the channel capacity of the main channel spanning from the source to the destination can be significantly increased with the aid of our TAS-SDPS scheme, which is converted into a secrecy improvement.

C. Transmit Antenna Selection Aided SD Pair Scheduling

This subsection proposes a transmit antenna selection aided source-destination pair selection (TAS-SDPS) scheme. In the TAS-SDPS scheme, the "best" antenna having the maximal achievable rate among all SD pairs in the set $\mathbb{D}$ will be chosen to access the shared spectrum for the sake of improving the security of the SNs's wireless transmissions. Therefore, based on (7), the SD pair selection scheme in the TAS-SDPS can be formulated as

$$\{s, a\} = \arg \max_{m \in \mathbb{D}, 1 \le i \le N_T} C_{s_{m_i} d_m}, \tag{10}$$

where s represents the index of the selected pair in the TAS-SDPS scheme, and a denotes the index of the chosen antenna of S_s, yielding:

$$\{s, a\} = \arg \max_{m \in \mathbb{D}, 1 \le i \le N_T} \sum_{j=1}^{N_R} \left| h_{s_{m_i} d_{m_j}} \right|^2. \tag{11}$$

More specifically, the TAS-SDPS scheme relies on the following steps:

Step1: The index s and a can be chosen either in a centralized or distributed manner [36].

Step2: Other SNs transmit their data to the sth SN selected. If the SN chosen successfully decodes a SN's data, it will forward its data during the second stage. Otherwise, the SN's data will not be forwarded.

Step3: S_s forwards its data and other SNs' data to D_s using time-division or frequency-division, and the received data at D_s will be retransmitted to the application center at last.

Therefore, the secrecy capacity of the S_s-D_s link under the TAS-SDPS scheme can be formulated as $C_{\text{TAS}}^s = C_{s_{s_a} d_s} - C_{s_s e}$. Furthermore, if $C_{s_k s_s} > R_o$, the secrecy capacity of the S_k-D_s link under the TAS-SDPS scheme can be formulated as $C_{\text{TAS}}^k = C_{s_{s_a} d_s} - C_{se}^{(k,m)}$, where R_o is the predefined data rate of S_k. Otherwise, the transmission from S_k to S_s is declined, and the secrecy capacity of the S_k-D_s link can be equivalent to that of the S_k-S_s link, thus, $C_{\text{TAS}}^k = C_{s_k s_s} - C_{s_k e}$.

Note that although secrecy beamforming can indeed improve the physical-layer security of wireless transmissions, this is achieved at the cost of increased implementation complexity, since beamforming requires high-complexity feedback and more radio frequency (RF) chains [31] and [32]. By contrast, TAS [25], [28]-[30] can be invoked for safeguarding wireless transmissions without depending on feedback and without many RF chains. Furthermore, as shown in Fig. 4, we have used space-time coding [25] and [28] for benchmarking purposes. One can observe from Fig. 4 that our TAS-SDPS scheme outperforms the space-time coding aided source-destination pair selection (STC-SDPS) scheme in terms of its SOP, showing the advantage of the TAS-SDPS scheme in terms of guarding wireless transmissions.

III. SECRECY OUTAGE PROBABILITY ANALYSIS

In this section, we present our performance analysis for the Non-coop, RSDPS, and TAS-SDPS schemes for transmission between SD pair over Rayleigh fading channels, whilst for transmission between SNs over Rician fading channels. The SOP expressions of the Non-coop as well as of the RSDPS and TAS-SDPS schemes are derived.

A. Conventional Non-coop Scheme

For comparison, the traditional non-cooperative (Non-coop) transmission scheme is also presented, wherein each SN communicates with its DN independently. As above mentioned, each SN respectively occupies the BHz channel bandwidth. The predefined secrecy rate of each SD pair is R_s. Hence, following [8] and [28], the SOP of the Non-coop scheme is expressed as

$$\begin{aligned} P_{\text{so}}^{\text{Non}} &= \frac{1}{M}\sum_{m=1}^{M} \Pr\left(B\log_2(1+\gamma_{s_m d_m}) - B\log_2(1+\gamma_{s_m e}) < R_s\right) \\ &= \frac{1}{M}\sum_{m=1}^{M} \Pr\left(\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}\left|h_{s_{m_i} d_{m_j}}\right|^2 < 2^{\frac{R_s}{B}} \sum_{i=1}^{N_T}\sum_{l=1}^{N_E}\left|h_{s_{m_i} e_l}\right|^2 + \Delta_0^{'}\right), \end{aligned} \tag{12}$$

where $\Delta_0^{'} = (2^{\frac{R_s}{B}} - 1) N_T N_0 / P_t$, and according to (A.6), $P_{\text{so}}^{\text{Non}}$ can be obtained as

$$\begin{aligned} P_{\text{so}}^{\text{Non}} = \frac{1}{M}\sum_{m=1}^{M} \Bigg(1 - \sum_{l=0}^{N_T N_R - 1}\sum_{p=0}^{l} \frac{(p + N_T N_E - 1)!}{p!\,(l-p)!\,(N_T N_E - 1)!} \left(\frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^{l} \\ \left(\frac{1}{\sigma_{me}^2}\right)^{N_T N_E} \left(\frac{\Delta_0^{'}}{2^{\frac{2R_s}{B}}}\right)^{l-p} \left(\frac{1}{\sigma_{me}^2} + \frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^{-p-N_T N_E} e^{-\frac{\Delta_0^{'}}{\sigma_{md}^2}}\Bigg). \end{aligned} \tag{13}$$

Observe from (12) and (13) that by definition, the conventional Non-coop scheme does not rely on any cooperation between the SD pairs. Furthermore, it does not take the CSI of the SNs-DNs links into account. Although the Non-coop scheme is of lower complexity, it may degrade the PLS of the wireless transmission. Hence, this motivates us to conceive a more sophisticated cooperative scheme for achieving SOP improvements.

B. Conventional RSDPS Scheme

This subsection provides the SOP analysis of the traditional RSDPS scheme used as a benchmarking scheme. In the conventional RSDPS scheme, each SD pair in the set $\mathbb{D}$ will be chosen to transmit with an equal probability. Therefore, according to [8] and [28], we can obtain the SOP of the signal arriving from S_m and S_k in the first as well as the second stage for the RSDPS scheme relying on the S_m-D_m pair formulated as

$$P_{\text{so\_m\_m}}^{\text{RSDPS}} = \Pr\left(C_{s_m d_m} - C_{s_m e} < R_s\right) \tag{14}$$

and

$$\begin{aligned} P_{\text{so\_k\_m}}^{\text{RSDPS}} = &\Pr\left(C_{s_m d_m} - C_{se}^{(k,m)} < R_s, C_{s_k s_m} > R_o\right) \\ &+ \Pr\left(C_{s_k s_m} - C_{s_k e} < R_s, C_{s_k s_m} < R_o\right), \end{aligned} \tag{15}$$

respectively. Upon combining (7) and (9), we arrive at

$$P_{\text{so\_m\_m}}^{\text{RSDPS}}=\Pr\left(\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}\left|h_{s_{m_i} d_{m_j}}\right|^2<2^{\frac{2R_s}{B}}\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}\left|h_{s_{m_i} e_l}\right|^2+\Delta_0\right) \tag{16}$$

and

$$\begin{aligned} P_{\text{so\_k\_m}}^{\text{RSDPS}} = &\Pr\left(\left|h_{s_k s_m}\right|^2 < 2^{\frac{2\cdot R_s}{B}}\sum_{l=1}^{N_E}\left|h_{s_k e_l}\right|^2+\Theta_1, \left|h_{s_k s_m}\right|^2<\Theta_0\right) \\ &+\Pr\left(\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}\left|h_{s_{m_i} d_{m_j}}\right|^2<\max\left(2^{\frac{2R_s}{B}}\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}\left|h_{s_{m_i} e_l}\right|^2, \right.\right. \\ &\left.\left.\frac{2^{\frac{2R_s}{B}}}{\Delta_1}\sum_{l=1}^{N_E}\left|h_{s_k e_l}\right|^2\right)+\Delta_0\right)\Pr\left(\left|h_{s_k s_m}\right|^2>\Theta_0\right), \end{aligned} \tag{17}$$

respectively, where we have $\Delta_0 = (2^{\frac{2\cdot R_s}{B}} - 1)N_T N_0/P_t$, $\Delta_1 = P_t/(P_s N_T)$, $\Theta_0 = (2^{\frac{2\cdot R_o}{B}} - 1)/\gamma_s$, $\Theta_1 = (2^{\frac{2\cdot R_s}{B}} - 1)/\gamma_s$. Furthermore, performing SD pair selection in the RSDPS scheme is independent of the random variables (RVs) $|h_{s_{m_i} d_{m_j}}|^2$ and $|h_{s_{m_i} e_l}|^2$. For simplicity, given the SD transmission pair m, we assume that the fading coefficients $|h_{s_{m_i} d_{m_j}}|^2$ for $i \in \{1,2,\cdots,N_T\}$, $j \in \{1,2,\cdots,N_R\}$, of all main channels are independent and identically distributed (i.i.d.) RVs with the same mean, denoted by $\sigma_{md}^2 = E(|h_{s_{m_i} d_{m_j}}|^2)$. Moreover, we also assume that the fading coefficients $|h_{s_{m_i} e_l}|^2$ for $i \in \{1,2,\cdots,N_T\}$, $l \in \{1,2,\cdots,N_E\}$, of all wiretap links are i.i.d RVs having the same average channel gain denoted by $\sigma_{me}^2 = E(|h_{s_{m_i} e_l}|^2)$, which is a common assumption widely used in the cooperative communication literature. Hence, according to (A.6) and (A.10), (16) and (17) can be obtained as

$$\begin{aligned} P_{\text{so\_m\_m}}^{\text{RSDPS}}=1-&\sum_{l=0}^{N_T N_R-1}\sum_{p=0}^{l}\frac{(p+N_T N_E-1)!}{p!\,(l-p)!\,(N_T N_E-1)!}\left(\frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^{l}\left(\frac{1}{\sigma_{me}^2}\right)^{N_T N_E} \\ &\left(\frac{\Delta_0}{2^{\frac{2R_s}{B}}}\right)^{l-p}\left(\frac{1}{\sigma_{me}^2}+\frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^{-p-N_T N_E} e^{-\frac{\Delta_0}{\sigma_{md}^2}} \end{aligned} \tag{18}$$

and

$$\begin{aligned} P_{\text{so\_k\_m}}^{\text{RSDPS}} =\bar{P}_{\text{o\_km}} &\left(\sum_{t=0}^{N_T N_E-1}\left(\frac{1}{\sigma_{ke}^2}\right)^{N_E}\left(\frac{1}{\sigma_{me}^2\Delta_1}\right)^{t}\frac{(t+N_E-1)!}{t!\,(N_E-1)!}c_{km}^{-t-N_E}\right. \\ &-\sum_{l=0}^{N_T N_R-1}\sum_{p=0}^{l}\sum_{t=0}^{p+N_T N_E-1}a_{lp}c_{md}\left(c_{km}+\frac{2^{\frac{2R_s}{B}}}{\Delta_1\sigma_{md}^2}\right)^{-t-N_E} \\ &+\sum_{t=0}^{N_E-1}\left(\frac{1}{\sigma_{me}^2}\right)^{N_T N_E}\left(\frac{\Delta_1}{\sigma_{ke}^2}\right)^{t}\frac{(t+N_T N_E-1)!}{t!\,(N_T N_E-1)!}d_{km}^{-t-N_T N_E} \\ &\left.-\sum_{l=0}^{N_T N_R-1}\sum_{p=0}^{l}\sum_{t=0}^{p+N_E-1}a_{lp}d_{kd}\left(d_{km}+\frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^{-t-N_T N_E}\right)+P_{\text{so\_km}}, \end{aligned} \tag{19}$$

respectively, where $\bar{P}_{\text{o\_km}}$ and $P_{\text{so\_km}}$ are given by (A.8) and (A.9), respectively. Hence, the SOP of all SD pairs investigated relying on S_m can be defined as

$$P_{\text{so\_m}}^{\text{RSDPS}} = \frac{1}{M}\left(\sum_{k\in\mathbb{D}-\{m\}}P_{\text{so\_k\_m}}^{\text{RSDPS}} + P_{\text{so\_m\_m}}^{\text{RSDPS}}\right). \tag{20}$$

As mentioned above, in the RSDPS scheme, each SD pair has an equal probability to be chosen. Furthermore, using the law of total probability [35], we can obtain the SOP for the RSDPS scheme as

$$P_{\text{so}}^{\text{RSDPS}} = \frac{1}{M}\sum_{m=1}^{M}P_{\text{so\_m}}^{\text{RSDPS}}. \tag{21}$$

It is observed from (14), (15) and (21) that although the RSDPS scheme relies on the cooperation between the set of SNs, it does not rely on the CSI knowledge of the SN-DN links. This implies that the employment of the TAS-SDPS scheme is capable of further enhancing the SOP in the wireless systems investigated.

C. Proposed TAS-SDPS Scheme

In this subsection, we present the SOP analysis of the TAS-SDPS scheme. As shown in (10), we can formulate the SOP of the signal impinging from S_s and S_k under the TAS-SDPS scheme with the aid of the S_s-D_s pair as

$$P_{\text{so\_s}}^{\text{TAS}} = \Pr\left(C_{s_{s_a} d_s} - C_{s_{s_a} e} < R_s\right) \tag{22}$$

and

$$\begin{aligned} P_{\text{so\_k}}^{\text{TAS}} = &\Pr\left(C_{s_{s_a} d_s} - C_{se}^{(k,s)} < R_s, C_{s_k s_s} > R_o\right) \\ &+ \Pr\left(C_{s_k s_s} - C_{s_k e} < R_s, C_{s_k s_s} < R_o\right), \end{aligned} \tag{23}$$

respectively.

Using (7)-(9), both (22) and (23) can be rewritten as

$$P_{\text{so\_s}}^{\text{TAS}} = \Pr\left(\sum_{j=1}^{N_R}\left|h_{s_{s_a}d_{s_j}}\right|^2 < 2^{\frac{2R_s}{B}}\sum_{l=1}^{N_E}\left|h_{s_{s_a}e_l}\right|^2 + \Lambda_0\right) \tag{24}$$

and

$$P_{\text{so\_k}}^{\text{TAS}}=\Pr\left(|h_{s_k s_s}|^2<2^{\frac{2\cdot R_s}{B}}\sum_{l=1}^{N_E}|h_{s_k e_l}|^2+\Theta_1, |h_{s_k s_s}|^2<\Theta_0\right) +\Pr\left(\sum_{j=1}^{N_R}\left|h_{s_{s_a}d_{s_j}}\right|^2<2^{\frac{2R_s}{B}}\max\left(\sum_{l=1}^{N_E}\left|h_{s_{s_a}e_l}\right|^2, \frac{1}{\Lambda_1}\sum_{l=1}^{N_E}|h_{s_k e_l}|^2+\Lambda_0\right)\right)\Pr\left(|h_{s_k s_s}|^2>\Theta_0\right), \tag{25}$$

respectively, where we have $\Lambda_0 = (2^{\frac{2\cdot R_s}{B}}-1)N_0/P_t$, and $\Lambda_1 = P_t/P_s$. Based on (11), we arrive at:

$$P_{\text{so\_s}}^{\text{TAS}}=\Pr\left(\max_{m\in\mathbb{D},1\leq i\leq N_T}\sum_{j=1}^{N_R}\left|h_{s_{m_i}d_{m_j}}\right|^2<2^{\frac{2R_s}{B}}\sum_{l=1}^{N_E}\left|h_{s_{m_i}e_l}\right|^2+\Lambda_0\right) \tag{26}$$

and

$$P_{\text{so\_k}}^{\text{TAS}}=\Pr\left(|h_{s_k s_m}|^2<2^{\frac{2\cdot R_s}{B}}\sum_{l=1}^{N_E}|h_{s_k e_l}|^2+\Theta_1, |h_{s_k s_m}|^2<\Theta_0\right) +\Pr\left(\max_{m\in\mathbb{D},1\leq i\leq N_T}\sum_{j=1}^{N_R}\left|h_{s_{m_i}d_{m_j}}\right|^2<2^{\frac{2R_s}{B}}\max\left(\sum_{l=1}^{N_E}\left|h_{s_{m_i}e_l}\right|^2, \frac{1}{\Lambda_1}\sum_{l=1}^{N_E}|h_{s_k e_l}|^2+\Lambda_0\right)\right)\Pr\left(|h_{s_k s_s}|^2>\Theta_0\right), \tag{27}$$

respectively.

Finally, using (A.11) and (A.12), both (26) and (27) can be obtained as

$$P_{\text{so\_s}}^{\text{TAS}} = \sum_{S'}\sum_{p=0}^{\beta_2}\Psi_0\left(p+N_E-1\right)!\left(\frac{1}{\sigma_{me}^2}+\beta_3 2^{\frac{2R_s}{B}}\right)^{-p-N_E} \tag{28}$$

and

$$P_{\text{so\_k}}^{\text{TAS}}=\bar{P}_{\text{o\_km}}\left(\sum_{S}\sum_{p=0}^{\beta_2}\sum_{t=0}^{p+N_E-1}a_{\beta p}c_{\beta d}\left(\frac{d_{km}'}{\Lambda_1}+\frac{\beta_3 2^{\frac{2R_s}{B}}}{\Lambda_1}\right)^{-t-N_E} +\sum_{S}\sum_{p=0}^{\beta_2}\sum_{t=0}^{p+N_E-1}a_{\beta p}d_{\beta d}\left(c_{km}'\Lambda_1+\beta_3 2^{\frac{2R_s}{B}}\right)^{-t-N_E}\right)+P_{\text{so\_km}}, \tag{29}$$

respectively. Moreover, relying on the definition in (20), the SOP of the investigated system relying on the proposed TAS-SDPS scheme can be expressed as:

$$P_{\text{so}}^{\text{TAS}} = \frac{1}{M}\left(\sum_{k\in\mathbb{D}-\{s\}}P_{\text{so\_k}}^{\text{TAS}}+P_{\text{so\_s}}^{\text{TAS}}\right). \tag{30}$$

So far, we have derived closed-form SOP expressions of the conventional Non-coop and RSDPS schemes as well as the proposed TAS-SDPS scheme.

IV. Secrecy Diversity Gain Analysis

In this section, we present the secrecy diversity analysis of the RSDPS and TAS-SDPS schemes in the high main-to-eavesdropper ratio (MER) region for the sake of providing further insights from (16), (17), (24) and (25) conceiving both the conventional RSDPS as well as the proposed TAS-SDPS scheme.

A. Traditional RSDPS Scheme

This subsection analyzes the asymptotic SOP of the conventional RSDPS scheme. In the spirit of [27], the traditional diversity gain is defined in [34] as

$$d = -\lim_{\text{SNR}\to\infty}\frac{\log P_{\text{e}}\left(\text{SNR}\right)}{\log \text{SNR}}, \tag{31}$$

which is used for characterizing the reliability of wireless communications, where SNR and $P_e(\text{SNR})$ denote the signal-to-noise ratio (SNR) of the destination node and the bit error ratio (BER), respectively. However, we can observe that the SOPs of the RSDPS and TAS-SDPS schemes are independent of the SNR, hence the definition of the traditional diversity gain may not perfectly suit our SOP analysis. Moreover, as shown in (16), (17), (24) and (25), the SOP of the RSDPS scheme is related to the main channel $|h_{s_{m_i}d_{m_j}}|^2$ as well as to the eavesdropping channels $|h_{s_{m_i}e_l}|^2$ and $|h_{s_k e_l}|^2$. For notational convenience, let $\lambda_{se} = \sigma_{md}^2/\sigma_{me}^2$ denote MER. In spirit of the above observation, and following [8] and [25], we define the secrecy diversity gain as the asymptotic ratio of the logarithmic SOP to the logarithmic λ_{se} as $\lambda_{se}\to\infty$, which is mathematically formulated as

$$d = -\lim_{\lambda_{se}\to\infty}\frac{\log\left(P_{\text{so}}\right)}{\log\left(\lambda_{se}\right)}. \tag{32}$$

Meanwhile, in (32), the SOP P_{so} behaves as λ_{se}^{-d} in the high MER region, which means that upon increasing the diversity gain d, P_{so} decreases faster in the high MER region. Using (32), the secrecy diversity gain of the RSDPS scheme can be expressed as

$$d_{\text{RSDPS}} = -\lim_{\lambda_{se}\to\infty}\frac{\log\left(P_{\text{so}}^{\text{RSDPS}}\right)}{\log\left(\lambda_{se}\right)}. \tag{33}$$

Theorem 1: The secrecy diversity gain of the RSDPS scheme is given by

$$d_{\text{RSDPS}} = N_T N_R. \tag{34}$$

Proof: Please refer to Appendix B.

Remark 1: We can observe from Theorem 1 that the RSDPS scheme only attains a secrecy diversity gain of $N_T N_R$, and the SOP of the RSDPS scheme is governed by the factor $(\frac{1}{\lambda_{se}})^{N_T N_R}$ in the high-MER region. This is due to the fact that the secrecy diversity gain of the RSDPS scheme only depends on the number of antennas invoked by a specific pair of the transmitters and receivers. Since d_{RSDPS} does not depend on the number of SD pairs, the RSDPS scheme achieves no SOP enhancement upon increasing the number of SD pairs, which is a disadvantage. Moreover, the secrecy diversity gain of the Non-coop scheme can also be shown to be given by $N_T N_R$.

B. Proposed TAS-SDPS Scheme

This subsection is focused on the secrecy diversity analysis of the TAS-SDPS scheme. Similarly to (33), the secrecy diversity order of the TAS-SDPS scheme can be expressed as

$$d_{\text{TAS}} = -\lim_{\lambda_{se}\to\infty} \frac{\log\left(P_{\text{so}}^{\text{TAS}}\right)}{\log\left(\lambda_{se}\right)}. \tag{35}$$

Theorem 2: The secrecy diversity gain of the TAS-SDPS scheme yields to

$$d_{\text{TAS}} = MN_T N_R. \tag{36}$$

Proof: Please refer to Appendix B.

Remark 2: Interestingly, we can see from Theorem 2 that the TAS-SDPS scheme achieves the secrecy diversity gain of $MN_T N_R$, which means that the SOP of the TAS-SDPS scheme is governed by the factor $(\frac{1}{\lambda_{se}})^{MN_T N_R}$ in the high-MER region. The SOP of the TAS-SDPS scheme can be improved not only by increasing the number of antennas of a transmitter and receiver pair, but also by increasing the number of the SD pairs. Therefore, the TAS-SDPS scheme advocated significantly outperforms both the conventional RSDPS and the Non-coop scheme in terms of their SOPs.

V. Performance Evaluation

In this section, we present our performance comparisons among the Non-coop, the RSDPS, the proposed TAS-SDPS schemes in terms of their SOPs and secrecy diversity gains. Specifically, the analytic SOPs of the Non-coop, the RSDPS, and TAS-SDPS schemes are evaluated by plotting (13), (21) and (30), respectively. Moreover, the lower bound SOPs of the RSDPS and TAS-SDPS schemes are obtained by using (B.15), and (B.21), respectively. The upper bound SOP of the RSDPS and TAS-SDPS schemes are obtained by using (B.18), and (B.23), respectively. The simulated SOP of the RSDPS as well as the proposed the TAS-SDPS schemes are also provided for demonstrating the correctness of the theoretical results. In our numerical evaluation, we assume that $\alpha_{s_{m_i}e_l} = \alpha_{s_k e_l} = \alpha_{s_{m_i}d_{m_j}} = 1$.

In Fig. 2, we show the SOP versus MER λ_{se} of both the traditional Non-coop and of the RSDPS as well as of the proposed TAS-SDPS schemes for different parameters (N_T, N_R, N_E) by plotting (13), (21) and (30), as a function of the MER λ_{se}. It is shown in Fig. 2 that the SOPs of the RSDPS, of the Non-coop, and of the TAS-SDPS schemes decrease, as the number of antennas (N_T, N_R, N_E) increases from $(N_T, N_R, N_E) = (1, 1, 1)$ to $(2, 2, 2)$. Furthermore, the RSDPS, the Non-coop, and the TAS-SDPS schemes using $(N_T, N_R, N_E) = (2, 2, 2)$ achieve better secrecy performance than that of $(N_T, N_R, N_E) = (1, 1, 1)$, respectively. Fig. 2 also demonstrates that increasing the MER upgrades the security of wireless transmissions in networks. Additionally, Fig. 2 demonstrates that the TAS-SDPS scheme attains the best SOP performance among the traditional RSDPS and Non-coop as well as the proposed TAS-SDPS schemes, when the MER increases from -10dB to 15dB.

Fig. 3 illustrates the SOP versus the SNR $\frac{P_t}{N_0}$ of the traditional RSDPS and of Non-coop as well as of the proposed TAS-SDPS schemes. Fig. 3 shows that increasing the SNR $\frac{P_t}{N_0}$ may moderately degrade the SOPs of the RSDPS, of the Non-coop as well as of the proposed TAS-SDPS schemes in the MER = 0dB case. By contrast, upon increasing the SNR, the SOPs of all schemes decreases are significantly reduced in the MER = 8dB case. This can be explained by observing that increasing the SNR is beneficial both for the SNs-DNs links and for the SNs-E links in the MER = 0dB case. However, increasing the SNR may be more beneficial for the SNs-DNs links than for the SNs-E links in the MER = 8dB case. Furthermore, it can also be seen from Fig. 3 that the SOP of the proposed TAS-SDPS scheme is lower than that of the RSDPS and Non-coop schemes at a specific SNR. In contrast to the Non-coop and RSDPS schemes, this means that the security performance benefits from exploiting the cooperation between the SD pairs by guarding against eavesdropping with the aid of proposed TAS-SDPS scheme.

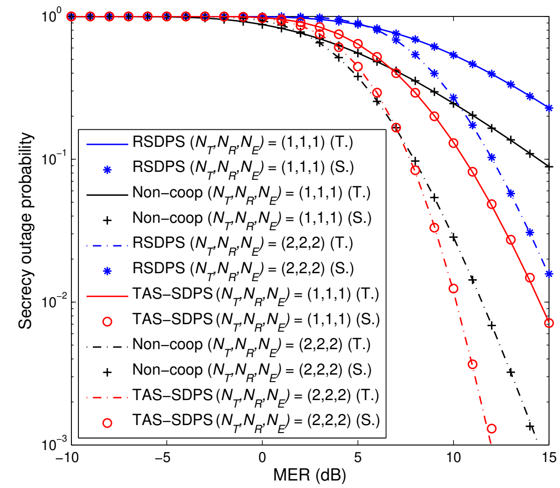

Fig. 2. SOP vs MER λ_{se} of the traditional Non-coop and RSDPS as well as the proposed TAS-SDPS schemes for different (N_T, N_R, N_E) with M = 4.

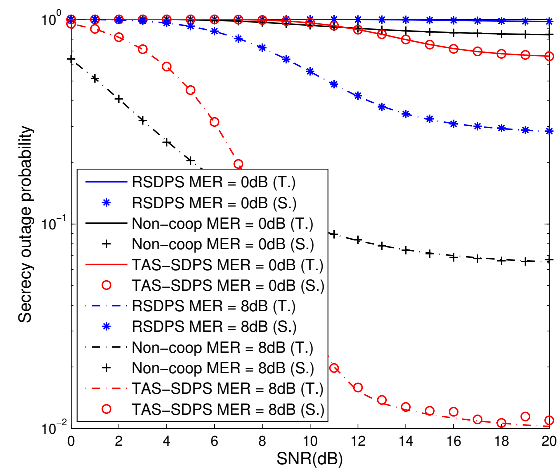

Fig. 3. SOP vs SNR $\frac{P_t}{N_0}$ of the traditional Non-coop and RSDPS as well as the proposed TAS-SDPS schemes for different MER with N_T = N_R = N_E = 2, and M = 8.

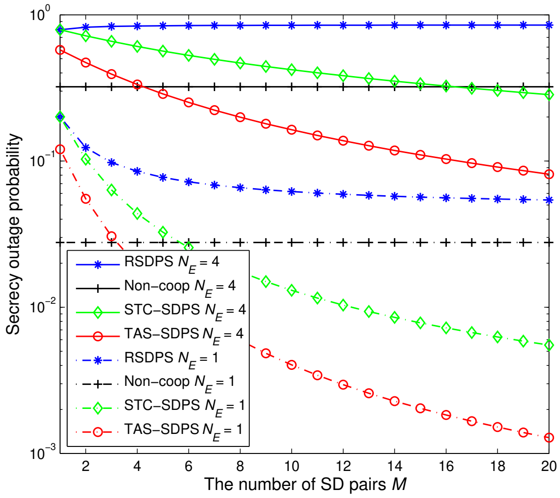

Fig. 4. SOP vs the number of source-destination pairs M of the traditional Non-coop, RSDPS, space-time coding [25] and [28] aided source-destination pair selection (STC-SDPS) as well as the proposed TAS-SDPS schemes for different N_E with N_T = N_R = 2, and λ_{se} = 8dB.

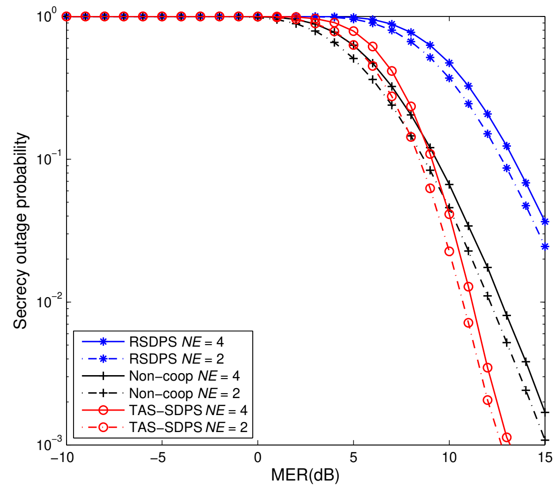

Fig. 6. SOP vs MER λ_{se} of the traditional Non-coop and RSDPS as well as the proposed TAS-SDPS schemes for different number of eavesdroppers NE with N_T = N_R = N_E = 2, and M = 4.

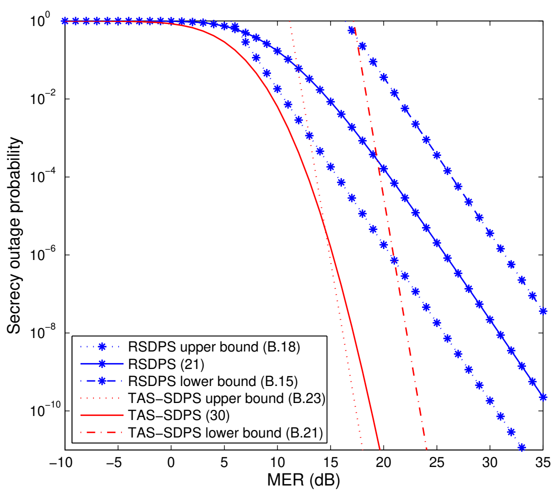

Fig. 5. Asymptotic and exact results on the SOP of the traditional RSDPS as well as the proposed TAS-SDPS schemes with N_T = N_R = N_E = 2, and M = 4.

Fig. 4 shows our SOP comparison of the traditional RSDPS and Non-coop as well as of the STC-SDPS and TAS-SDPS schemes for different number of SD pairs M. Observe that the SOP of the signal arriving from S_s and S_k under the STC-SDPS scheme with the aid of the S_s-D_s pair can be formulated as $P_{\text{so\_s}}^{\text{STC}} = \Pr(C_{s_sd_s} - C_{s_se} < R_s)$ and $P_{\text{so\_k}}^{\text{STC}} = \Pr(C_{s_sd_s} - C_{se}^{(\bar{k},s)} < R_s, C_{s_ks_s} > R_o) + \Pr(C_{s_ks_s} - C_{s_ke} < R_s, C_{s_ks_s} < R_o)$, respectively, where $s = \arg\max_{m\in\mathbb{D}} \sum_{i=1}^{N_T}\sum_{j=1}^{N_R} |h_{s_{m_i}d_{m_j}}|^2$, and following [25] and [28], we have $C_{s_sd_s} = \frac{B}{2}\log_2(1+\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}\frac{P_t|h_{s_{s_i}d_{s_j}}|^2}{N_TN_0})$ and $C_{s_se} = \frac{B}{2}\log_2(1+\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}\frac{P_t|h_{s_{s_i}e_l}|^2}{N_TN_0})$. Observe from Fig. 4 that as the number of SD pairs increases from M = 2 to 20, the SOPs of the TAS-SDPS and of the STC-SDPS schemes are significantly reduced, which shows that increasing the number of SD pairs is beneficial for the PLS of the TAS-SDPS and STC-SDPS schemes, both in the cases of N_e = 1 and N_e = 4. This is due to the fact that when M increases from M = 2 to 20, the proposed TAS-SDPS and STC-SDPS schemes can take advantage of the cooperation between different SD pairs for enhancing the PLS of wireless networks. However, the SOPs of the RSDPS and of the Non-coop schemes remain unchanged, when the number of SD pairs increases from M = 2 to 20. Moreover, upon increasing N_e, the SOPs of the TAS-SDPS and of the STC-SDPS schemes can be updated by increasing the number SD pairs M. As shown in Fig. 4, the proposed TAS-SDPS scheme outperforms both the Non-coop, as well as the RSDPS and the STC-SDPS schemes in terms of their SOPs, explicitly quantifying the advantage of the proposed TAS-SDPS scheme in terms of safeguarding wireless transmissions between the source-destination pairs.

Fig. 5 shows both the asymptotic and the exact results conceiving the SOP of the traditional RSDPS as well as of the proposed TAS-SDPS schemes, where the lower bound results, exact results and the upper bound results are obtained by plotting (B.15), (B.21), (21), (30), (B.18), and (B.23) as a function of the MER, respectively. Observe from Fig. 5 that the exact SOP curves of the RSDPS, and the TAS-SDPS schemes are more and more close to their corresponding lower and upper bounds, as the MER increases. Moreover, as shown in Fig. 5, in the high-MER region, the exact SOP curves of the RSDPS, and TAS-SDPS schemes exhibit the same slopes of their corresponding lower and upper bounds, respectively. This demonstrates the correctness of our secrecy diversity gain analysis of the RSDPS, and TAS-SDPS schemes in the high-MER region.

Fig. 6 depicts the SOP versus MER λ_{se} of both the traditional Non-coop and of the RSDPS as well as of the proposed

TAS-SDPS schemes for different number of eavesdroppers NE, where $\gamma_{s_k e}$ and $\gamma_{s_m e}$ in (4) and (8) are given by $\max\limits_{1\leq j\leq NE}\sum\limits_{l=1}^{N_E}\frac{P_s|h_{s_k e_{j_l}}|^2}{N_0}$ and $\max\limits_{1\leq j\leq NE}\sum\limits_{l=1}^{N_E}\frac{P_t|h_{s_{m_i} e_{j_l}}|^2}{N_0}$, respectively. Observe from Fig. 6 that as the number of eavesdroppers increases from $NE = 2$ to 4, the SOPs of the RSDPS, of the Non-coop, and of the TAS-SDPS schemes decrease accordingly. Moreover, observe in Fig. 6 that the proposed TAS-SDPS scheme outperforms the RSDPS and the Non-coop schemes in terms of their SOPs, demonstrating that the proposed TAS-SDPS scheme is still capable of guaranteeing the PLS of wireless transmissions in the face of multiple eavesdroppers.

VI. Conclusions

In this paper, we explored a wireless network coexisting with multiple SD pairs in the face of an eavesdropper, where each SD pair may access the shared spectrum dynamically, and the eavesdropper aims for maliciously wiretapping the signals transmitted by the source nodes. We proposed a cooperative framework relying on two stages for enhancing the PLS of the ongoing wireless transmissions, wherein an SD pair will be chosen as the transmitting pair from the perspective of security. Moreover, we presented an SD pair selection scheme, termed as the TAS-SDPS. We analyzed the SOP of the proposed TAS-SDPS scheme, and carried out the SOP analysis of both the RSDPS and of the Non-coop schemes as a baseline. We also carried out the secrecy diversity gain analysis of the TAS-SDPS scheme, as well as of the RSDPS scheme. It was demonstrated that the TAS-SDPS scheme outperforms both the RSDPS and the Non-coop schemes in terms of its SOP. Furthermore, as the number of SD pairs increases, the SOP of the TAS-SDPS scheme improves, while the SOPs of the RSDPS and Non-coop schemes remain unchanged.

Appendix A

Upon defining $U = \sum\limits_{i=1}^{N_T}\sum\limits_{j=1}^{N_R}|h_{s_{m_i} d_{m_j}}|^2$, $X_1 = \sum\limits_{i=1}^{N_T}\sum\limits_{l=1}^{N_E}|h_{s_{m_i} e_l}|^2$, $X_2 = \sum\limits_{l=1}^{N_E}|h_{s_k e_l}|^2$, and $X_3 = |h_{s_k s_m}|^2$, and taking into account that the RVs $|h_{s_{m_i} d_{m_j}}|^2$, $|h_{s_k e_l}|^2$, $|h_{s_{m_i} e_l}|^2$, and $|h_{s_k s_m}|^2$ are independent of each other, $P_{\text{so\_m\_m}}^{\text{RSDPS}}$ and $P_{\text{so\_k\_m}}^{\text{RSDPS}}$ can be expressed as

$$P_{\text{so\_m\_m}}^{\text{RSDPS}} = \int_0^{\infty} F_U\left(\Delta_0 + 2^{\frac{2R_s}{B}}x_1\right) f_{X_1}(x_1)\, dx_1 \tag{A.1}$$

and

$$P_{\text{so\_k\_m}}^{\text{RSDPS}} = \bar{P}_{\text{o\_km}}\left(\int_0^{\infty}\int_{\frac{x_2}{\Delta_1}}^{\infty} F_U\left(\Delta_0 + 2^{\frac{2R_s}{B}}x_1\right) f_{X_1}(x_1) f_{X_2}(x_2)\, dx_1 dx_2 + \int_0^{\infty}\int_{\Delta_1 x_1}^{\infty} F_U\left(\Delta_0 + \frac{2^{\frac{2R_s}{B}}}{\Delta_1}x_2\right) f_{X_2}(x_2) f_{X_1}(x_1)\, dx_2 dx_1\right) + P_{\text{so\_km}}, \tag{A.2}$$

respectively, where $F_U(u)$ is the cumulative distribution function (CDF) of RV U, $f_{X_1}(x_1)$ and $f_{X_2}(x_2)$ are respective the probability density functions (PDFs) of the RVs X_1 and X_2, $\bar{P}_{\text{o\_km}} = \Pr(|h_{s_k s_m}|^2 > \Theta_0)$, and $P_{\text{so\_km}} = \Pr(|h_{s_k s_m}|^2 < 2^{\frac{2\cdot R_s}{B}}\sum\limits_{l=1}^{N_E}|h_{s_k e_l}|^2 + \Theta_1, |h_{s_k s_m}|^2 < \Theta_0)$. For simplicity, we assume that for different m, i, j, l, k, $\sigma_{s_{m_i} d_{m_j}}^2 = \sigma_{md}^2$, $\sigma_{s_{m_i} e_l}^2 = \sigma_{me}^2$, and $\sigma_{s_k e_l}^2 = \sigma_{me}^2$. Based on [9], they can be expressed as:

$$F_U\left(\Delta_0 + 2^{\frac{2R_s}{B}}x_1\right) = 1 - \exp\left(-\frac{\Delta_0 + 2^{\frac{2R_s}{B}}x_1}{\sigma_{md}^2}\right)\sum_{l=0}^{N_T N_R - 1}\frac{1}{l!}\left(\frac{\Delta_0 + 2^{\frac{2R_s}{B}}x_1}{\sigma_{md}^2}\right)^l \tag{A.3}$$

and

$$f_{X_1}(x_1) = \frac{{x_1}^{N_T N_E - 1}}{(N_T N_E - 1)!}\left(\frac{1}{\sigma_{me}^2}\right)^{N_T N_E}\exp\left(-\frac{x_1}{\sigma_{me}^2}\right) \tag{A.4}$$

and

$$f_{X_2}(x_2) = \frac{{x_2}^{N_E - 1}}{(N_E - 1)!}\left(\frac{1}{\sigma_{ke}^2}\right)^{N_E}\exp\left(-\frac{x_2}{\sigma_{ke}^2}\right), \tag{A.5}$$

respectively. Substituting (A.3) and (A.4) into (A.1) yields

$$\begin{aligned} P_{\text{so\_m\_m}}^{\text{RSDPS}} &= \int_0^{\infty} F_U\left(\Delta_0 + 2^{\frac{2R_s}{B}}x_1\right) f_{X_1}(x_1)\, dx_1 \\ &= 1 - \sum_{l=0}^{N_T N_R - 1}\sum_{p=0}^{l}\frac{(p + N_T N_E - 1)!}{p!\,(l-p)!\,(N_T N_E - 1)!}\left(\frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^l\left(\frac{1}{\sigma_{me}^2}\right)^{N_T N_E} \\ &\quad \left(\frac{\Delta_0}{2^{\frac{2R_s}{B}}}\right)^{l-p}\left(\frac{1}{\sigma_{me}^2} + \frac{2^{\frac{2R_s}{B}}}{\sigma_{md}^2}\right)^{-p - N_T N_E} e^{-\frac{\Delta_0}{\sigma_{md}^2}}. \end{aligned} \tag{A.6}$$

Relying on [33], the PDF of RV X_3 can be approximated as

$$f_{X_3}(x_3) = \left(\frac{m_{s_k s_m}}{\sigma_{s_k s_m}^2}\right)^{m_{s_k s_m}}\frac{{x_3}^{m_B - 1}}{\Gamma(m_{s_k s_m})}\exp\left(-\frac{m_{s_k s_m}x_3}{\sigma_{s_k s_m}^2}\right), \tag{A.7}$$

where $m_{s_k s_m} = \frac{(1+K_{s_k s_m})^2}{2K_{s_k s_m}+1}$, and $\sigma_{s_k s_m}^2$ denotes the average power of $|h_{s_k s_m}|^2$. Hence, $\bar{P}_{\text{o\_km}}$ and $P_{\text{so\_km}}$ can be further formulated as

$$\begin{aligned} \bar{P}_{\text{o\_km}} &= \int_{\Theta_0}^{\infty}\left(\frac{m_{s_k s_m}}{\sigma_{s_k s_m}^2}\right)^{m_{s_k s_m}}\frac{{x_3}^{m_{s_k s_m} - 1}}{\Gamma(m_{s_k s_m})}\exp\left(-\frac{m_{s_k s_m}x_3}{\sigma_{s_k s_m}^2}\right)dx_3 \\ &= \sum_{g=0}^{m_{s_k s_m} - 1}\frac{(\Theta_0)^g}{g!}\exp\left(-\frac{\Theta_0 m_{s_k s_m}}{\sigma_{s_k s_m}^2}\right)\left(\frac{m_{s_k s_m}}{\sigma_{s_k s_m}^2}\right)^g \end{aligned} \tag{A.8}$$

and

$$P_{\text{so\_km}} = \begin{cases} \int_0^{\Theta_0} f_{X_3}(x_3)dx_3, & \text{if } R_s \geq R_o \\ \int_0^{\Theta_0} f_{X_3}(x_3)dx_3 \int_0^{\Theta_2} f_{X_2}(x_2)dx_2 + \int_0^{\Theta_2}\int_0^{2^{\frac{2R_s}{B}}x_2 + \Theta_1} f_{X_2}(x_2) f_{X_3}(x_3)dx_3 dx_2, & \text{otherwise} \end{cases}$$

$$
= \begin{cases}
1-\sum\limits_{g=0}^{m_{s_k s_m}-1}\frac{(\Theta_0)^g}{g!}\exp\left(-\frac{\Theta_0 m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)\left(\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)^g, \ \text{if} \ R_s \geq R_o \\
\left(1-\sum\limits_{g=0}^{m_{s_k s_m}-1}\frac{(\Theta_0)^g}{g!}\exp\left(-\frac{\Theta_0 m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)\left(\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)^g\right)\left(\sum\limits_{g=0}^{N_E-1}\frac{1}{g!}\left(\frac{\Theta_2}{\sigma^2_{me}}\right.\right. \\
\left.\left.\exp\left(-\frac{\Theta_2}{\sigma^2_{me}}\right)\right)^g\right)+\Theta_3\Theta_4\left((N_E-1)!\left(\frac{1}{\sigma^2_{me}}\right)^{-N_E}-\exp\left(-\frac{\Theta_2}{\sigma^2_{me}}\right)\right. \\
\left.\sum\limits_{g=0}^{N_E-1}\frac{(N_E-1)!}{g!}(\Theta_2)^g\left(\frac{1}{\sigma^2_{me}}\right)^{N_E-g}\right)-\sum\limits_{g=0}^{m_{s_k s_m}-1}\sum\limits_{p=0}^{g}\frac{(N_E-1)!\Theta_4}{p!(g-p)!} \\
\left(\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)^{-m_{s_k s_m}+g}\left(\frac{2^{\frac{2R_s}{B}}-1}{\gamma_s 2^{\frac{2R_s}{B}}}\right)^{g-p}\exp\left(-\frac{\left(2^{\frac{2R_s}{B}}-1\right)m_{s_k s_m}}{\gamma_s\sigma^2_{s_k s_m}}\right) \\
\left(\frac{\left(2^{\frac{2R_s}{B}}\right)^g(p+N_E-1)!}{\left(\frac{1}{\sigma^2_{me}}+2^{\frac{2R_s}{B}}\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)^{p+N_E}}-\sum\limits_{l=0}^{p+N_E-1}\frac{(p+N_E-1)!(\Theta_2)^l}{l!\left(\frac{1}{\sigma^2_{me}}+2^{\frac{2R_s}{B}}\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)^{p+N_E-l}}\right. \\
\left.\exp\left(-\Theta_2\left(\frac{1}{\sigma^2_{me}}+2^{\frac{2R_s}{B}}\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}}\right)\right)\right), \text{otherwise}
\end{cases} \quad \text{(A.9)}
$$

respectively, where $\Theta_2 = \frac{1}{2^{\frac{2R_s}{B}}}(\Theta_0 - \Theta_1)$, $\Theta_3 = \frac{(m_{s_k s_m}-1)!\sigma^{2m_{s_k s_m}}_{s_k s_m}}{(m_{s_k s_m})^{m_{s_k s_m}}}$, and $\Theta_4 = \frac{1}{(N_E-1)!\Gamma(m_{s_k s_m})}(\frac{1}{\sigma^2_{me}})^{N_E}(\frac{m_{s_k s_m}}{\sigma^2_{s_k s_m}})^{m_{s_k s_m}}$. Furthermore, substituting (A.3)-(A.5), (A.8) and (A.9) into (A.2) yields

$$
\begin{aligned}
P^{\text{RSDPS}}_{\text{so\_k\_m}} =& \bar{P}_{\text{o\_km}}\left(\sum_{t=0}^{N_T N_E-1}\left(\frac{1}{\sigma^2_{ke}}\right)^{N_E}\left(\frac{1}{\sigma^2_{me}\Delta_1}\right)^t\frac{(t+N_E-1)!}{t!\,(N_E-1)!}c_{km}^{-t-N_E}\right. \\
&-\sum_{l=0}^{N_T N_R-1}\sum_{p=0}^{l}\sum_{t=0}^{p+N_T N_E-1}a_{lp}c_{md}\left(c_{km}+\frac{2^{\frac{2R_s}{B}}}{\Delta_1\sigma^2_{md}}\right)^{-t-N_E} \\
&+\sum_{t=0}^{N_E-1}\left(\frac{1}{\sigma^2_{me}}\right)^{N_T N_E}\left(\frac{\Delta_1}{\sigma^2_{ke}}\right)^t\frac{(t+N_T N_E-1)!}{t!\,(N_T N_E-1)!}d_{km}^{-t-N_T N_E} \\
&\left.-\sum_{l=0}^{N_T N_R-1}\sum_{p=0}^{l}\sum_{t=0}^{p+N_E-1}a_{lp}d_{kd}\left(d_{km}+\frac{2^{\frac{2R_s}{B}}}{\sigma^2_{md}}\right)^{-t-N_T N_E}\right)+P_{\text{so\_km}}, \quad \text{(A.10)}
\end{aligned}
$$

where $a_{lp} = \frac{(\frac{1}{\sigma^2_{ke}})^{N_E}(\frac{1}{\sigma^2_{me}})^{N_T N_E}(\frac{2^{\frac{2R_s}{B}}}{\sigma^2_{md}})^l(\frac{\Delta_0}{2^{\frac{2R_s}{B}}})^{l-p}e^{-\frac{\Delta_0}{\sigma^2_{md}}}}{p!(l-p)!t!(N_E-1)!(N_T N_E-1)!}$, $c_{md} = (\frac{1}{\sigma^2_{me}}+\frac{2^{\frac{2R_s}{B}}}{\sigma^2_{md}})^{-p-N_T N_E+t}\Delta_1^{-t}(p+N_T N_E-1)!(t+N_E-1)!$, $d_{kd} = (\frac{1}{\sigma^2_{ke}}+\frac{2^{\frac{2R_s}{B}}}{\Delta_1\sigma^2_{md}})^{-p-N_E+t}\Delta_1^{t-p}(t+N_T N_E-1)!(p+N_E-1)!$, $c_{km} = \frac{1}{\sigma^2_{ke}}+\frac{1}{\Delta_1\sigma^2_{me}}$, and $d_{km} = \frac{\Delta_1}{\sigma^2_{ke}}+\frac{1}{\sigma^2_{me}}$.

Moreover, defining $Q = \sum_{j=1}^{N_R}|h_{s_{m_i}d_{m_j}}|^2$, $W_1 = \sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2$, and $W_2 = \sum_{l=1}^{N_E}|h_{s_k e_l}|^2$, and exploiting that the RVs Q, W_1 and W_2 are independent of each other, after further integral operation, $P^{\text{TAS}}_{\text{so\_s}}$ and $P^{\text{TAS}}_{\text{so\_k}}$ can be obtained as

$$
\begin{aligned}
P^{\text{TAS}}_{\text{so\_s}} =& \sum_{S'}\sum_{p=0}^{\beta_2}\int_0^\infty\Psi_0 w^{p+N_E-1}\exp\left(-\frac{w}{\sigma^2_{me}}-\beta_3 2^{\frac{2R_s}{B}}w\right)dw \\
=& \sum_{S'}\sum_{p=0}^{\beta_2}\Psi_0\,(p+N_E-1)!\left(\frac{1}{\sigma^2_{me}}+\beta_3 2^{\frac{2R_s}{B}}\right)^{-p-N_E} \quad \text{(A.11)}
\end{aligned}
$$

and

$$
\begin{aligned}
P^{\text{TAS}}_{\text{so\_k}} =& \bar{P}_{\text{o\_km}}\left(\sum_{S}\sum_{p=0}^{\beta_2}\sum_{t=0}^{p+N_E-1}a_{\beta p}c_{\beta d}\left(\frac{d'_{km}}{\Lambda_1}+\frac{\beta_3 2^{\frac{2R_s}{B}}}{\Lambda_1}\right)^{-t-N_E}\right. \\
&\left.+\sum_{S}\sum_{p=0}^{\beta_2}\sum_{t=0}^{p+N_E-1}a_{\beta p}d_{\beta d}\left(c'_{km}\Lambda_1+\beta_3 2^{\frac{2R_s}{B}}\right)^{-t-N_E}\right)+P_{\text{so\_km}}, \quad \text{(A.12)}
\end{aligned}
$$

respectively, where $\beta_1 = \frac{(|\mathbb{D}|\cdot N_T)!}{\prod_{i=1}^{N_R+1}n_i!}\prod_{j=1}^{N_R}(-\frac{1}{\sigma^{2(j-1)}_{md}(j-1)!})^{n_j}$, $\beta_2 = \sum_{j=1}^{N_R}n_j(j-1)$, $S' = \{(n_1, n_2, \cdots, n_{N_R+1})|\sum_{i=1}^{N_R+1}n_i = |\mathbb{D}|\cdot N_T\}$, $\beta_3 = \frac{1}{\sigma^2_{md}}(|\mathbb{D}|\cdot N_T - n_{N_R+1})$, and $\Psi_0 = \frac{\beta_1}{(N_E-1)!}\binom{\beta_2}{p}(\frac{1}{\sigma^2_{me}})^{N_E}(2^{\frac{2R_s}{B}})^{\beta_2}(\frac{\Lambda_0}{2^{\frac{2R_s}{B}}})^{\beta_2-p}e^{-\beta_3\Lambda_0}$. Moreover, $a_{\beta p} = \frac{(\frac{1}{\sigma^2_{ke}})^{N_E}(\frac{1}{\sigma^2_{me}})^{N_E}(2^{\frac{2R_s}{B}})^p(\Lambda_0)^{\beta_2-p}\beta_1(\beta_2)!e^{-\Lambda_0\beta_3}}{p!(\beta_2-p)!t!(N_E-1)!(N_E-1)!}$, $c_{\beta d} = (\frac{1}{\sigma^2_{me}}+2^{\frac{2R_s}{B}}\beta_3)^{-p-N_E+t}\Lambda_1^{-t}(p+N_E-1)!(t+N_E-1)!$, $c'_{km} = \frac{1}{\sigma^2_{ke}}+\frac{1}{\Lambda_1\sigma^2_{me}}$, $d'_{km} = \frac{\Lambda_1}{\sigma^2_{ke}}+\frac{1}{\sigma^2_{me}}$, and $d_{\beta d} = (\frac{1}{\sigma^2_{ke}}+\frac{2^{\frac{2R_s}{B}}\beta_3}{\Lambda_1})^{-p-N_E+t}\Lambda_1^{t-p}(t+N_E-1)!(p+N_E-1)!$.

APPENDIX B

A, Proof of Theorem 1:

Upon utilizing (16), (17), and the inequality $\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}|h_{s_{m_i}d_{m_j}}|^2 \leq N_T N_R\max_{i,j}|h_{s_{m_i}d_{m_j}}|^2$, $2^{\frac{2R_s}{B}}\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2 + \Delta_0 \geq 2^{\frac{2R_s}{B}}\max_{i,l}|h_{s_{m_i}e_l}|^2$, and $2^{\frac{2R_s}{B}}\max(\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2, \frac{1}{\Delta_1}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2) + \Delta_0 \geq 2^{\frac{2R_s}{B}}\max(\max_{i,l}|h_{s_{m_i}e_l}|^2, \frac{1}{\Delta_1}\max_{l}|h_{s_k e_l}|^2)$, we have

$$
\begin{aligned}
P^{\text{RSDPS}}_{\text{so}} \geq& \frac{1}{M}\sum_{m=1}^{M}\frac{1}{M}\left(\Pr\left(N_T N_R\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < 2^{\frac{2R_s}{B}}\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2\right)\right. \\
&+\sum_{k\in\mathbb{D}-\{m\}}\Pr\left(N_T N_R\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < 2^{\frac{2R_s}{B}}\max\left(\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2,\right.\right. \\
&\left.\left.\left.\frac{1}{\Delta_1}\max_{l}|h_{s_k e_l}|^2\right)\right)\right)\bar{P}_{\text{o\_km}}. \quad \text{(B.1)}
\end{aligned}
$$

Defining $X_1 = \max_{i,l}|h_{s_{m_i}e_l}|^2$, $X_2 = \max_{i,l}|h_{s_k e_l}|^2$, and $Y = \max_{i,l}|h_{s_{m_i}d_{m_j}}|^2$, the expressions $\Pr(\max_{i,j}|h_{s_{m_i}d_{m_j}}|^2 < 2^{\frac{2R_s}{B}}\frac{1}{N_T N_R}\max_{i,l}|h_{s_{m_i}e_l}|^2)$ and $\Pr(\max_{i,j}|h_{s_{m_i}d_{m_j}}|^2 < 2^{\frac{2R_s}{B}}\frac{1}{N_T N_R}\max(\max_{i,l}|h_{s_{m_i}e_l}|^2, \frac{1}{\Delta_1}\max_{l}|h_{s_k e_l}|^2))$ can be rewritten as

$$
\begin{aligned}
&\Pr\left(\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < \frac{2^{\frac{2R_s}{B}}}{N_T N_R}\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2\right) \\
&= \int_0^\infty\prod_{i,j}F_Y\left(\frac{2^{\frac{2R_s}{B}}x_1}{N_T N_R}\right)f_{X_1}(x_1)\,dx_1 \quad \text{(B.2)}
\end{aligned}
$$

and

$$\Pr\left(\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < \frac{2^{\frac{2R_s}{B}}}{N_T N_R}\max\left(\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2, \frac{1}{\Delta_1}\max_{l}\left|h_{s_k e_l}\right|^2\right)\right)$$
$$= \int_0^\infty \int_{\frac{x_2}{\Delta_1}}^\infty \prod_{i,j} F_Y\left(\frac{2^{\frac{2R_s}{B}} x_1}{N_T N_R}\right) f_{X_1}(x_1) f_{X_2}(x_2)\, dx_1 dx_2$$
$$+ \int_0^\infty \int_{\Delta_1 x_1}^\infty \prod_{i,j} F_Y\left(\frac{2^{\frac{2R_s}{B}} x_2}{N_T N_R \Delta_1}\right) f_{X_2}(x_2) f_{X_1}(x_1)\, dx_2 dx_1, \quad (B.3)$$

respectively, where $F_Y(y)$ is the CDF of the RV Y, while $f_{X_1}(x_1)$ and $f_{X_2}(x_2)$ are the PDFs of the RVs X_1 and X_2, respectively. Noting that the RVs $|h_{s_{m_i}e_l}|^2$ and $|h_{s_k e_l}|^2$ obey the exponential distribution and are independent of each other, $i = 1, 2, \cdots, N_T$, $l = 1, 2, \cdots, N_E$, the CDF of X_1 can be expressed as:

$$\Pr(X < x) = \Pr\left(\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2 < x\right) = \prod_{i,l}\Pr\left(\left|h_{s_{m_i}e_l}\right|^2 < x\right)$$
$$= 1 + \sum_{n=1}^{2^{N_T N_E}-1}(-1)^{|C_n|}\exp\left(-\sum_{i,l\in C_n}\frac{x}{\sigma^2_{s_{m_i}e_l}}\right), \quad (B.4)$$

where $|C_n|$ is the cardinality of the set C_n, and C_n denotes the n-th non-empty subset of C. Moreover, C represents the set of the links spanning from the SNs to the eavesdropper E in the second stage. Hence, the PDF of the RV X_1 can be formulated as

$$f_{X_1}(x_1) = \sum_{n=1}^{2^{N_T N_E}-1}\sum_{i,l\in C_n}\frac{(-1)^{|C_n|+1}}{\sigma^2_{s_{m_i}e_l}}\exp\left(-\sum_{i,l\in C_n}\frac{x_1}{\sigma^2_{s_{m_i}e_l}}\right). \quad (B.5)$$

Similarly to (B.5), the PDF of the RV X_2 is given by

$$f_{X_2}(x_2) = \sum_{n=1}^{2^{N_E}-1}\sum_{l\in F_g}\frac{(-1)^{|F_g|+1}}{\sigma^2_{s_k e_l}}\exp\left(-\sum_{l\in F_g}\frac{x_2}{\sigma^2_{s_k e_l}}\right), \quad (B.6)$$

where $|F_g|$ represents the cardinality of the set F_g, and F_g is the g-th non-empty subset of F. Moreover, F denotes the set of the links spanning from the SNs to the eavesdropper E in the first stage. Furthermore, $\prod_{i,j} F_Y(\frac{2^{\frac{2R_s}{B}} x_1}{N_T N_R})$ can be expanded as

$$\prod_{i,j} F_Y\left(\frac{2^{\frac{2R_s}{B}} x_1}{N_T N_R}\right) = \prod_{i,j}\left(1 - \exp\left(-\frac{2^{\frac{2R_s}{B}}}{N_T N_R}\frac{x_1}{\sigma^2_{s_{m_i}d_{m_j}}}\right)\right). \quad (B.7)$$

For notational convenience, we introduce $Z_1 = -\frac{2^{\frac{2R_s}{B}}}{N_T N_R}\frac{x_1}{\sigma^2_{s_{m_i}d_{m_j}}}$, and $Z_2 = -\frac{2^{\frac{2R_s}{B}}}{N_T N_R}\frac{x_2}{\Delta_1 \sigma^2_{s_{m_i}d_{m_j}}}$. Then, $E(Z_1)$ is given by

$$E(Z_1) = \int_0^\infty \int_{\frac{x_2}{\Delta_1}}^\infty \left(\frac{2^{\frac{2R_s}{B}}}{N_T N_R}\frac{x_1}{\sigma^2_{s_{m_i}d_{m_j}}}\right) f_{X_1}(x_1) f_{X_2}(x_2)\, dx_1 dx_2$$
$$= \sum_{n=1}^{2^{N_T N_E}-1}\sum_{g=1}^{2^{N_E}-1}\sum_{t=0}^{1}\left(\frac{1}{\Delta_1}\right)^t \frac{2^{\frac{2R_s}{B}} a_{ngt}(-1)^{|C_n|+|F_g|}}{N_T N_R (1-t)!}\frac{1}{\lambda_{se}}, \quad (B.8)$$

where $a_{ngt} = \frac{(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{t-1}(\sum_{l\in F_g}\frac{1}{\alpha_{s_k e_l}})(-\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}} - \sum_{l\in F_g}\frac{1}{\alpha_{s_k e_l}})^{-t-1}}{\alpha_{s_{m_i}d_{m_j}}}$.

Upon considering $\lambda_{se} \to \infty$, $E(Z_1)$ tends to zero. Similarly, $E(Z_2)$, $E((Z_1)^2)$ and $E((Z_2)^2)$ also tend to zero, when $\lambda_{se} \to \infty$. Thus, based on [25], $1 - \exp(-\frac{1}{N_T N_R}\frac{2^{\frac{2R_s}{B}} x}{\sigma^2_{s_{m_i}d_{m_j}}})$ can be simplified to

$$1 - \exp\left(-\frac{1}{N_T N_R}\frac{2^{\frac{2R_s}{B}} x}{\sigma^2_{s_{m_i}d_{m_j}}}\right) \overset{1}{=} \frac{2^{\frac{2R_s}{B}}}{N_T N_R}\frac{x}{\sigma^2_{s_{m_i}d_{m_j}}}. \quad (B.9)$$

Hence, $\prod_{i,j} F_Y(\frac{2^{\frac{2R_s}{B}} x_1}{N_T N_R})$ and $\prod_{i,j} F_Y(\frac{2^{\frac{2R_s}{B}} x_2}{\Delta_1 N_T N_R})$ can be rewritten as

$$\prod_{i,j} F_Y\left(\frac{2^{\frac{2R_s}{B}} x_1}{N_T N_R}\right) = \left(\frac{2^{\frac{2R_s}{B}}}{N_T N_R}\right)^{N_T N_R}\prod_{i,j}\frac{1}{\sigma^2_{s_{m_i}d_{m_j}}} x^{N_T N_R} \quad (B.10)$$

and

$$\prod_{i,j} F_Y\left(\frac{2^{\frac{2R_s}{B}} x_1}{\Delta_1 N_T N_R}\right) = \left(\frac{2^{\frac{2R_s}{B}}}{\Delta_1 N_T N_R}\right)^{N_T N_R}\prod_{i,j}\frac{1}{\sigma^2_{s_{m_i}d_{m_j}}} x^{N_T N_R}, \quad (B.11)$$

respectively. Substituting (B.4) and (B.9) into (B.2) yields

$$\Pr\left(N_T N_R \max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < 2^{\frac{2R_s}{B}}\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2\right)$$
$$= \sum_{n=1}^{2^{N_T N_E}-1}\left(\frac{2^{\frac{2R_s}{B}}}{N_T N_R}\right)^{N_T N_R}(N_T N_R)!(-1)^{|C_n|+1}\left(\sum_{i,l\in C_n}\frac{1}{\sigma^2_{s_i e_l}}\right)^{-N_T N_R}\prod_{i,j}\frac{1}{\sigma^2_{s_{m_i}d_{m_j}}}, \quad (B.12)$$

which can be further rewritten as

$$\Pr\left(N_T N_R \max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < 2^{\frac{2R_s}{B}}\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2\right)$$
$$= \sum_{n=1}^{2^{N_T N_E}-1}(-1)^{|C_n|+1}\omega_{il0}\left(\frac{1}{\lambda_{se}}\right)^{N_T N_R}, \quad (B.13)$$

where $\omega_{il0} = (N_T N_R)!(\frac{2^{\frac{2R_s}{B}}}{N_T N_R})^{N_T N_R}(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{-N_T N_R}(\prod_{i,j}\alpha_{s_{m_i}d_{m_j}})^{-1}$.

Similarly to (B.13), (B.3) can be finally obtained as

$$\Pr\left(\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2 < \frac{2^{\frac{2R_s}{B}}}{N_T N_R}\max\left(\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2, \frac{1}{\Delta_1}\max_{l}\left|h_{s_k e_l}\right|^2\right)\right)$$
$$= \sum_{n=1}^{2^{N_T N_E}-1}\sum_{g=1}^{2^{N_E}-1}\sum_{t=0}^{N_T N_R}(-1)^{|C_n|+|F_g|}\alpha_{il0}\left(\frac{1}{\lambda_{se}}\right)^{N_T N_R}$$
$$+ \sum_{n=1}^{2^{N_T N_E}-1}\sum_{g=1}^{2^{N_E}-1}\sum_{t=0}^{N_T N_R}(-1)^{|C_n|+|F_g|}\beta_{il0}\left(\frac{1}{\lambda_{se}}\right)^{N_T N_R}, \quad (B.14)$$

where $\alpha_{il0} = \frac{(\sum_{l\in F_g}\frac{1}{\alpha_{s_k e_l}})(N_T N_R)!\prod_{i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(\frac{2^{\frac{2R_s}{B}}}{N_T N_R})^{N_T N_R}}{(N_T N_R - t)!(\Delta_1)^t(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{N_T N_R - k}(\alpha'_{il0})^{t+1}}$,

$\beta_{il0} = \frac{(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})(N_T N_R)!\prod_{i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(\frac{2^{\frac{2R_s}{B}}}{N_T N_R \Delta_1})^{N_T N_R}}{(N_T N_R - t)!(\Delta_1)^{-t}(\sum_{l\in F_g}\frac{1}{\alpha_{s_k e_l}})^{N_T N_R - k}(\Delta_1\alpha'_{il0})^{t+1}}$, and

$\alpha'_{il0} = \sum_{i,l\in C_n}\frac{1}{\Delta_1 \alpha_{s_{m_i}e_l}} + \sum_{l\in F_g}\frac{1}{\alpha_{s_k e_l}}$.

Based on (B.13) and (B.14), (B.1) can be reformulated as (B.15) shown at the top of the following page.

$$P_{\rm so}^{\rm RSDPS}\geq\frac{1}{M}\sum_{m=1}^{M}\left(\frac{1}{M}\left(\sum_{n=1}^{2^{N_TN_E-1}}(-1)^{|C_n|+1}\omega_{il0}+\sum_{n=1}^{2^{N_TN_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{N_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\alpha_{il0}+\sum_{n=1}^{2^{N_TN_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{N_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\beta_{il0}\right)\right)\left(\frac{1}{\lambda_{se}}\right)^{N_TN_R}. \tag{B.15}$$

$$P_{\rm so}^{\rm RSDPS}\leq\frac{1}{M}\sum_{m=1}^{M}\left(\frac{1}{M}\left(\sum_{n=1}^{2^{N_TN_E-1}}(-1)^{|C_n|+1}\omega_{il1}+\sum_{n=1}^{2^{N_TN_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{N_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\alpha_{il1}+\sum_{n=1}^{2^{N_TN_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{N_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\beta_{il1}\right)\right)\left(\frac{1}{\lambda_{se}}\right)^{N_TN_R}. \tag{B.18}$$

Combining (33) and (B.15) yields

$$d_{\rm RSDPS} \leq N_TN_R. \tag{B.16}$$

Furthermore, in the high-SNR region we can observe from the definition of Δ_0 that as the transmit power P_t tends to infinity, Δ_0 approaches zero. Substituting the inequality $\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}|h_{s_{m_i}d_{m_j}}|^2 \geq \max_{i,j}|h_{s_{m_i}d_{m_j}}|^2$, $2^{\frac{2R_s}{B}}\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2 + \Delta_0 \leq 2^{\frac{2R_s}{B}}N_TN_E\max_{i,l}|h_{s_{m_i}e_l}|^2$, and $2^{\frac{2R_s}{B}}\max(\sum_{i=1}^{N_T}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2, \frac{1}{\Delta_1}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2) + \Delta_0 \leq 2^{\frac{2R_s}{B}}\max(N_TN_E\max_{i,l}|h_{s_{m_i}e_l}|^2, \frac{N_E}{\Delta_1}\max_{l}|h_{s_ke_l}|^2)$ into (16) and (17) yields

$$P_{\rm so}^{\rm RSDPS}\leq\frac{1}{M}\sum_{m=1}^{M}\frac{1}{M}\left(\Pr\left(\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2<2^{\frac{2R_s}{B}}N_TN_E\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2\right)\right.$$
$$+\sum_{k\in\mathbb{D}-\{m\}}\Pr\left(\max_{i,j}\left|h_{s_{m_i}d_{m_j}}\right|^2<2^{\frac{2R_s}{B}}\max\left(N_TN_E\max_{i,l}\left|h_{s_{m_i}e_l}\right|^2,\right.\right.$$
$$\left.\left.\left.\frac{N_E}{\Delta_1}\max_{l}\left|h_{s_ke_l}\right|^2\right)\right)\right)\bar{P}_{\rm o\_km}. \tag{B.17}$$

Similarly to (B.15), (B.17) can be reformulated as (B.18) shown at the top of the following page, where $\omega_{il1} = (N_TN_R)!(2^{\frac{2R_s}{B}}N_TN_E)^{N_TN_R}(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{-N_TN_R}(\prod_{i,j}\alpha_{s_{m_i}d_{m_j}})^{-1}$,
$\alpha_{il1} = \frac{(\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}})\prod_{i,j}\frac{1}{(N_TN_R)!\alpha_{s_{m_i}d_{m_j}}}(2^{\frac{2R_s}{B}}N_TN_E)^{N_TN_R}}{(N_TN_R-t)!(N_T\Delta_1)^t(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{N_TN_R-k}(\alpha'_{il1})^{t+1}}$,
$\alpha'_{il1} = \sum_{i,l\in C_n}\frac{1}{N_T\Delta_1\alpha_{s_{m_i}e_l}}+\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}}$, and $\beta_{il1} = \frac{(\sum_{i,l\in C_n}\frac{1}{(N_TN_R)!\alpha_{s_{m_i}e_l}})\prod_{i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(\frac{2^{\frac{2R_s}{B}}N_E}{\Delta_1})^{N_TN_R}}{(N_TN_R-t)!(\Delta_1N_T)^{-t}(\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}})^{N_TN_R-k}(\Delta_1N_T\alpha'_{il1})^{t+1}}$.

Moreover, substituting (B.18) into (33) yields

$$d_{\rm RSDPS} \geq N_TN_R. \tag{B.19}$$

Therefore, based on (B.16) and (B.19), the secrecy diversity gain of the conventional RSDPS scheme can be expressed as

$$d_{\rm RSDPS} = N_TN_R. \tag{B.20}$$

B, Proof of Theorem 2:

Considering the inequality $2^{\frac{2R_s}{B}}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2 + \Lambda_0 \geq 2^{\frac{2R_s}{B}}\max_{l}|h_{s_{m_i}e_l}|^2$, $\max_{m\in\mathbb{D},1\leq i\leq N_T}\sum_{j=1}^{N_R}|h_{s_{m_i}d_{m_j}}|^2\leq N_R\max_{m,i,j}|h_{s_{m_i}d_{m_j}}|^2$, and $2^{\frac{2R_s}{B}}\max(\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2,\frac{1}{\Lambda_1}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2) + \Lambda_0 \geq 2^{\frac{2R_s}{B}}\max(\max_{l}|h_{s_{m_i}e_l}|^2, \frac{1}{\Lambda_1}\max_{l}|h_{s_ke_l}|^2)$, through further integral operation, we arrive at (B.21) shown at the top of the following page, where $\omega_{mil2} = (MN_TN_R)!(\frac{2^{\frac{2R_s}{B}}}{N_R})^{MN_TN_R}(\sum_{i,l\in C_n}\frac{1}{\alpha_{s_ie_l}})^{-MN_TN_R}(\prod_{i,j}\alpha_{s_{m_i}d_{m_j}})^{-1}$,
$\alpha_{mil2} = \frac{(MN_TN_R)!(\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}})\prod_{m,i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(\frac{2^{\frac{2R_s}{B}}}{N_R})^{MN_TN_R}}{(MN_TN_R-t)!(\Lambda_1)^t(\sum_{l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{MN_TN_R-t}(\alpha'_{il2})^{t+1}}$,
$\alpha'_{il2} = \sum_{l\in C_n}\frac{1}{\Lambda_1\alpha_{s_{m_i}e_l}}+\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}}$, and $\beta_{mil2} = \frac{(MN_TN_R)!(\sum_{l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})\prod_{m,i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(\frac{2^{\frac{2R_s}{B}}}{N_R\Lambda_1})^{MN_TN_R}}{(MN_TN_R-t)!(\Lambda_1)^{-t}(\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}})^{MN_TN_R-t}(\Lambda_1\alpha'_{il2})^{t+1}}$. Substituting (B.21) into (35) yields

$$d_{\rm TAS} \leq MN_TN_R. \tag{B.22}$$

Furthermore, upon considering an infinite SNR and using the inequality $\max_{m\in\mathbb{D},1\leq i\leq N_T}\sum_{j=1}^{N_R}|h_{s_{m_i}d_{m_j}}|^2\geq\max_{m,i,j}|h_{s_{m_i}d_{m_j}}|^2$, $2^{\frac{2R_s}{B}}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2 + \Lambda_0 \leq 2^{\frac{2R_s}{B}}N_E\max_{l}|h_{s_{m_i}e_l}|^2$, and $2^{\frac{2R_s}{B}}\max(\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2, \frac{1}{\Lambda_1}\sum_{l=1}^{N_E}|h_{s_{m_i}e_l}|^2) + \Lambda_0 \leq 2^{\frac{2R_s}{B}}\max(N_E\max_{l}|h_{s_{m_i}e_l}|^2, \frac{N_E}{\Lambda_1}\max_{l}|h_{s_ke_l}|^2)$, similarly to (B.21), we arrive at (B.23) shown at the top of the following page, where $\alpha_{mil3} = \frac{(MN_TN_R)!(\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}})\prod_{m,i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(2^{\frac{2R_s}{B}}N_E)^{MN_TN_R}}{(MN_TN_R-t)!(\Lambda_1)^t(\sum_{l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{MN_TN_R-t}(\alpha'_{il2})^{t+1}}$, $\omega_{mil3} = (MN_TN_R)!(2^{\frac{2R_s}{B}}N_E)^{MN_TN_R}(\sum_{l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})^{-MN_TN_R}(\prod_{m,i,j}\alpha_{s_{m_i}d_{m_j}})^{-1}$
and $\beta_{mil3} = \frac{(MN_TN_R)!(\sum_{l\in C_n}\frac{1}{\alpha_{s_{m_i}e_l}})\prod_{m,i,j}\frac{1}{\alpha_{s_{m_i}d_{m_j}}}(\frac{2^{\frac{2R_s}{B}}N_E}{\Lambda_1})^{MN_TN_R}}{(MN_TN_R-t)!(\Lambda_1)^{-t}(\sum_{l\in F_g}\frac{1}{\alpha_{s_ke_l}})^{MN_TN_R-t}(\Lambda_1\alpha'_{il2})^{t+1}}$.

Hence, upon using (35) and (B.23), we obtain

$$d_{\rm TAS} \geq MN_TN_R. \tag{B.24}$$

By combining (B.22) and (B.24), we arrive at the secrecy diversity gain of the proposed TAS-SDPS scheme as

$$d_{\rm TAS} = MN_TN_R. \tag{B.25}$$

$$P_{\rm so}^{\rm TAS}\geq\frac{1}{M}\left(\sum_{n=1}^{2^{N_E-1}}(-1)^{|C_n|+1}\omega_{mil2}+\sum_{n=1}^{2^{N_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{MN_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\alpha_{mil2}+\sum_{n=1}^{2^{N_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{MN_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\beta_{mil2}\right)\left(\frac{1}{\lambda_{se}}\right)^{MN_TN_R}. \quad \text{(B.21)}$$

$$P_{\rm so}^{\rm TAS}\leq\frac{1}{M}\left(\sum_{n=1}^{2^{N_E-1}}(-1)^{|C_n|+1}\omega_{mil3}+\sum_{n=1}^{2^{N_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{MN_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\alpha_{mil3}+\sum_{n=1}^{2^{N_E-1}}\sum_{g=1}^{2^{N_E-1}}\sum_{t=0}^{MN_TN_R}(-1)^{|C_n|+|F_g|}\bar{P}_{\rm o\_km}\beta_{mil3}\right)\left(\frac{1}{\lambda_{se}}\right)^{MN_TN_R}. \quad \text{(B.23)}$$

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