Secrecy Outage and Diversity Analysis of Spectrum-Sharing Heterogeneous Wireless Systems

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Abstract

We study the physical-layer security of a spectrum-sharing heterogeneous wireless network in the face of an eavesdropper, which is composed of multiple source-destination (SD) pairs, where an eavesdropper intends to wiretap the signal transmitted by the SD pairs. In order to protect the wireless transmission against eavesdropping, we propose a heterogeneous cooperation framework relying on two stages. Specifically, an SD pair is selected to access the shared spectrum using an appropriately designed scheme at the beginning of the first stage. The other source nodes (SNs) transmit their data to the SN of the above-mentioned SD pair through a reliable short-range wireless interface 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, which in turn will forward all the other DNs’ data to the corresponding DNs via the backhaul. We conceive two specific SD pair selection schemes, termed as space-time coding aided source-destination pair selection (STC-SDPS),

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and the transmit antenna selection aided source-destination pair selection (TAS-SDPS), respectively. We derive the secrecy outage probability (SOP) expressions for both the STC-SDPS and for the TAS-SDPS schemes. Furthermore, we carry out the secrecy diversity gain analysis in the high main-to-eavesdropper ratio (MER) region, showing that both the STC-SDPS and TAS-SDPS schemes are capable of achieving the maximum attainable secrecy diversity order. Additionally, increasing the number of the heterogeneous transmission pairs will reduce the SOP, whilst increasing the secrecy diversity order of the STC-SDPS and TAS-SDPS schemes. For comparison, we also carry out both the SOP and the secrecy diversity order analysis of the traditional round-robin source-destination pair selection (RSDPS) scheme. The SOP analysis of the conventional non-cooperation (Non-coop) scheme is also presented, where each SD pair transmits independently. It is shown that the SOPs of the STC-SDPS and TAS-SDPS schemes are better than those of RSDPS and Non-coop schemes. We also demonstrate that the secrecy diversity gains of proposed STC-SDPS and TAS-SDPS schemes are $M$ times that of the RSDPS scheme in the high-MER region, where $M$ is the number of the SD pairs.

**Index Terms**

Heterogeneous wireless network, physical-layer security, source-destination pair scheduling, secrecy diversity gain.

**I. INTRODUCTION**

Heterogeneous wireless networks can access the same spectrum resource dynamically with the aid of spectrum sharing techniques [1], [2], which are capable of increasing the system’s efficiency and flexibility, whilst reducing their deployment cost. Recently, the spectrum sharing concept has also been extended to the fifth-generation (5G) systems [3], [4], wherein the licensed and unlicensed spectrum can be flexibly utilized to improve the quality of experience. However, heterogeneous 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. Hence, we have to protect the heterogeneous wireless networks against malicious eavesdropping.

Physical-layer security [5]-[7] 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 [8], [9] for reducing the secrecy outage probability. Similarly, beamforming techniques were also invoked for improving the secrecy of wireless transmissions [10] and [11]. Moreover, the concept of cognitive jamming was explored in [12], while specially designed artificial noise was used for preventing eavesdropping in [13]. Furthermore, the authors of [14] and [15] explored opportunistic user scheduling conceived with cooperative jamming. More specifically, in [15], 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 [16], [17] and two-way [18], [19] relying schemes were conceived for guarding against eavesdropping, demonstrating that relay selection schemes are capable of improving the physical-layer security. This is indeed expected, because they improve the quality of the desired link.

As a further development, physical-layer security has also been designed for heterogeneous wireless networks, supporting a multiplicity of diverse devices. Hence, more efforts should be invested in enhancing the physical-layer security of heterogeneous wireless networks. The secrecy beamforming concept has been proposed by Lv et al. [20] for improving the physical-layer security of heterogeneous networks. Moreover, jamming schemes have been investigated in [21] and [22]. To be specific, in [21], 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. A comprehensive performance analysis of artificial-noise aided secure multi-antenna transmission relying on a stochastic geometry framework was provided in [22] for $K$-tier heterogeneous cell networks. In [23], antenna selection was used for improving the security of source-destination transmissions.
in a multiple antenna aided MIMO system consisting of one source, one destination and one eavesdropper. Furthermore, the co-existence of a macro cell and a small cell constituting a simple heterogeneous cellular network was investigated by Zou [24]. 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 [25], Tolossa et al. investigated the base-station-user association scenarios suitable for protecting the ongoing transmission between the base-station and the intended user against eavesdropping. Additionally, the achievable average secrecy rate was analyzed by exploiting the association both with the “best” and with the $k$th best base-stations.

Against this backdrop, in this paper, we explore the physical-layer security of a heterogeneous wireless network comprised of multiple source-destination (SD) pairs in the presence of an eavesdropper. In contrast to [20]-[25], we investigate the cooperation between different SD pairs for safeguarding against malicious eavesdropping with the aid of a specifically designed cooperative framework, and the main differences between this paper and [20]-[25] are summarized in table 1. Moreover, we propose a pair of cooperation schemes based on source-destination (SD) pair scheduling. More explicitly, against this background, the main contributions of this paper are summarized as follows.

1) Firstly, we propose a heterogeneous 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, other source nodes (SNs) will confidentially transmit their data to the chosen SN via a high-reliability low-power auxiliary sub-system. In the second stage, the specifically chosen SN transmits the repacked data to its destination node (DN), which will forward the received packets to the DNs of the other SNs via the secure backhaul.

2) Secondly, we present two specific transmission selection schemes. The first one is termed
as the space-time coding aided source-destination pair scheduling (STC-SDPS), while the second one is referred to as the transmit antenna selection aided source-destination pair scheduling (TAS-SDPS). To be specific, an SD pair having the maximal channel capacity will be regarded as the transmission pair with the aid of the shared spectrum in the STC-SDPS scheme. By contrast, in the TAS-SDPS scheme, the “best” antenna of a chosen SD pair will be selected to transmit the repacked data relying on the shared spectrum.

3) Thirdly, we analyze the secrecy outage probability (SOP) of the proposed STC-SDPS and TAS-SDPS schemes for transmission over Rayleigh fading channels. We also evaluate the SOP of the traditional round-robin transmission pair scheduling (RSDPS) scheme for comparison. Moreover, we evaluate the secrecy diversity gains of both the STC-SDPS and TAS-SDPS schemes as well as the RSDPS scheme, demonstrating that the STC-SDPS and TAS-SDPS schemes are capable of achieving the full secrecy diversity gain.

4) Finally, it is shown that the SOPs of the STC-SDPS and TAS-SDPS schemes will be beneficially reduced by increasing the number of SD transmission pairs. Furthermore, the STC-SDPS and TAS-SDPS schemes outperform the RSDPS scheme in terms of both the SOP and the secrecy diversity gain attained, demonstrating that the advantages of the proposed heterogeneous cooperative framework improves the security of wireless communications.

The organization of this paper is as follows. In Section II, we briefly characterize the physical-layer security of a heterogeneous wireless network. In Section III, we carry out the SOP analysis of the RSDPS, STC-SDPS and TAS-SDPS schemes communicating over a Rayleigh channel. In Section IV we evaluate the secrecy diversity gain of the proposed STC-SDPS and TAS-SDPS schemes as well as of the RSDPS scheme. Our performance evaluations are detailed in Section VI. Finally, in Section V we conclude the paper.
| Feature                                      | Our work | [20] | [21] | [22] | [23] | [24] | [25] |
|----------------------------------------------|----------|------|------|------|------|------|------|
| Heterogeneous wireless network               | ✓        |      |      |      |      |      | ✓    |
| Cooperative framework                        | ✓        |      |      |      |      |      |      |
| Spectrum-sharing                             | ✓        | ✓    |      |      |      |      | ✓    |
| BS with multiple antennas                    | ✓        | ✓    |      |      |      |      | ✓    |
| User with multiple antennas                  | ✓        |      |      |      |      |      |      |
| STC-SDPS scheme                              | ✓        |      |      |      |      |      |      |
| TAS-SDPS scheme                              | ✓        |      |      |      |      |      |      |
| Secrecy outage probability                   | ✓        |      |      |      |      |      |      |
| Secrecy diversity gain                       | ✓        |      |      |      |      |      |      |
| Beamforming                                  | ✓        |      |      |      | ✓    |      |      |
| Jamming                                      | ✓        |      |      |      |      | ✓    |      |
| Secrecy rate                                 | ✓        |      |      |      |      |      | ✓    |
| Zero secrecy capacity                         |          |      |      |      |      |      |      |
| Connection probability and secrecy probability| ✓        |      |      |      |      |      |      |
| Against eavesdropping                        | ✓        | ✓    |      |      |      |      |      |

Table 1 Comparisons between our work and the related works [20]-[25]

Fig. 1. A heterogeneous wireless network consisting of Fig. 2. Two stages of the proposed cooperation framework $M$ multiple source-destination pairs in the presence of an for a heterogeneous wireless network, eavesdropper E.

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, where an SD is denoted by $S_i$. This source node (SN) communicates with its corresponding destination node (DN) via the dynamically shared spectrum, $i \in \{1, \cdots, M\}$, as well as with the other SNs via a reliable short-range interface (e.g., Zigbee, Bluetooth, etc.), since we assume that the distance between any two SNs is short. For notational convenience,
we let \( D \) represent the set of the SD pairs. The eavesdropper is denoted by \( E \), which intends to wiretap the legitimate SD pairs with the aid of a wide-band receiver. All nodes are assumed to be equipped with multiple antennas. All DNs are connected via a backhaul [26], which has the ability of exchanging the signals received from the DNs. Moreover, both the main and the wiretap links are modeled by Rayleigh fading [17], where the channel gains of the main links (spanning from the legitimate transmitter to its legitimate receiver) and the wiretap links (spanning from the legitimate transmitter to the eavesdropper) are denoted by \( h_{s_{mi}d_{mj}} \), \( h_{s_{mi}e_{l}} \), \( m, k \in \{1, \ldots, M\}, k \neq m, i \in \{1, \ldots, N_{T}\}, j \in \{1, \ldots, N_{R}\}, l \in \{1, \ldots, N_{E}\} \), respectively, where \( N_{T}, N_{R}, \) and \( N_{E} \) denote the number of transmit antennas of \( S_{i} \), \( D_{i} \), and \( E \), respectively.

The heterogeneous cooperative framework relies on two stages, as illustrated in Fig. 2. To be specific, an SD pair will be chosen to dynamically access the shared spectrum according to two specific SD scheduling schemes at the beginning of the first stage, where the SD scheduling schemes only consider the links transmitting between the SNs and DNs, without considering the transmitting links between SNs. This is due to the fact that the SNs communicate with each other with the aid of a high-reliability low-power system, hence the outage probability of the links between a pair of SNs is lower than that of the SNs-DNs links. Moreover, in order to help other pairs transmit their data, the chosen SD pair will receive the data of the other nodes through a high-reliability short-range system, and repack the successfully decoded data and its own data. As illustrated in Fig. 2, the sub-packet of a pair is comprised of three parts, which include the index of the SD pair, the length of the repacked data, and the repacked data. In the second stage, the specifically selected SN transmits the packet to its DN. After decoding the packet, the DN forwards the sub-packets to the other DNs relying on the index of the pair in the sub-packet via a high-speed backhaul.
B. Signal Model

In the first stage, let us assume that the SN $S_m$ is selected as the transmitting node. As mentioned above, other SNs will transmit their signal to $S_m$ via a high-reliability low-power system with the aid of a single antenna. Thus, the signal received at $S_m$ transmitted by $S_k$, $k \in D - \{m\}$, is given by:

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

(1)

where $P_s$, $x_k$, $h_{s_k s_m}$ and $n_{s_m}$ denotes the transmitted power of $S_k$ relying on a high-reliability low-power system, the transmitted signal of $s_k$, the channel gain of the $S_k$-$S_m$ link having zero mean and variance of $\sigma_{s_k s_m}^2$, and the thermal noise received at the $S_m$, respectively.

In the meantime, the signal transmitted by $S_k$ will be overheard by E, which can be expressed as

$$y_{s_k e_l} = \sqrt{P_s} h_{s_k e_l} x_s + n_{e_l},$$

(2)

where $n_{e_l}$ represents the thermal noise received at E.

From (1) and (2), the channel capacity of the $S_k$-$S_m$ and $S_k$-E links can be expressed as

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

(3)

and

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

(4)

respectively, where $\gamma_{s_k s_m} = \frac{P_s |h_{s_k s_m}|^2}{N_0}$, $\gamma_{s_k e} = \sum_{l=1}^{N_E} \frac{P_s |h_{s_k e_l}|^2}{N_0}$, and $B$ denotes the channel bandwidth.

In the second stage, $S_m$ transmits the packet $x_s$. Thus, the signal received at $D_m$ can be formulated as

$$y_{s_m d_m} = \sqrt{P_{tx}} h_{s_m d_m} x_s + n_{d_m},$$

(5)

where $P_{tx}$ and $n_{d_m}$ denote the transmitted power of $S_m$, and the thermal noise received at
the $S_m$, respectively. In the space-time coding (STC) case, for simplicity, we assume that the transmitted power of each antenna of $S_m$ is equal, thus, $P_{tx} = \frac{P_t}{N_T}$, where $P_t$ represents the available transmit power of each SN. By contrast, we have $P_{tx} = P_t$ in the transmit antenna selection (TAS) case.

Similarly to (3), the signal transmitted by $S_m$ will be overheard by E, which can be written as

$$y_{sm,e_l} = \sqrt{P_{tx}} h_{sm,e_l} x_s + n_{e_l}. \tag{6}$$

Relying on (5), the instantaneous channel capacity of the $S_m-D_m$ and of the $S_m-D_m$ links in the STC and TAS cases can be formulated as

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

and

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

respectively, where $\gamma_{sm,d_m} = \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \frac{P_t |h_{sm_i,d_m,j}|^2}{N_T N_0}$, $\gamma_{sm_i,d_m} = \sum_{j=1}^{N_R} \frac{P_t |h_{sm_i,d_m,j}|^2}{N_0}$, and $N_0$ denotes the variance of thermal noise $n_{d_m,j}$ and $n_{e_l}$.

Using (6), the instantaneous channel capacity of the $S_m$-E links can be expressed as

$$C_{sm,e} = \frac{B}{2} \log_2 \left(1 + \gamma_{sm,e} \right), \tag{9}$$

where $\gamma_{sm,e} = \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \frac{P_t |h_{sm,e,l}|^2}{N_T N_0}$ in the STC case, and $\gamma_{sm,e} = \sum_{l=1}^{N_E} \frac{P_t |h_{sm,e,l}|^2}{N_0}$ in the TAS case.

Using (4) and (9), the overall capacity of the link spanning from $S_k$, $k \in D - \{m\}$, the wiretap channel from $S_m$-E and $S_k$-E can be obtained by using the maximum of the individual channel capacity of these two links in the first and second stages, i.e.

$$C_{sm,e} = \max \left(C_{sm,e}^k, C_{sm,e}^m \right) = \frac{B}{2} \log_2 \left[1 + \max \left(\gamma_{sm,e}, \gamma_{sk,e} \right) \right]. \tag{10}$$

As mentioned above, given the chosen transmission pair, the signal of the chosen SD will only
be transmitted during the second stage. By contrast, the signal of other SDs will be transmitted both during the first state and be forwarded in the second stage. Hence, the signal of the other SDs 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 maximal ratio combining (MRC). Moreover, as discussed in [16], when independent and different codewords are used in the two stages, MRC becomes inapplicable, whereas SC is still suitable for the E.

C. Space-Time Coding Aided SD Scheduling

In this subsection, we propose a space-time coding aided source-destination scheduling (STC-SDPS) scheme for the sake of improving the security of the SDs’s wireless transmissions, wherein an SD pair having the instantaneous channel capacity $C_{s_m d_m}$ will be selected, yielding

$$s = \arg \max_{m \in D} \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_m i d_m j}|^2,$$

where $s$ denotes the index of the selected pair in the proposed STC-SDPS scheme. Hence, the secrecy capacity of the $S_k-D_k$ and $S_s-D_s$ links in the STC-SDPS scheme is given by $C_{STC}^{s_k} = C^{s_k}_{S_k D_k} - C^{s_k}_{S_k E}$ and $C_{STC}^{s} = C^{s}_{S_s D_s} - C^{s}_{S_s E}$, respectively.

D. Transmit Antenna Selection Aided SD Pair Scheduling

This subsection proposes a transmit antenna selection aided source-destination pair scheduling (TAS-SDPS) scheme. In the TAS-SDPS scheme, the “best” antenna having the maximal channel capacity of all SDs in the set $D$ will be chosen to access the shared spectrum for the sake of improving the security of the SDs’ wireless transmissions. Therefore, based on (7), the SD pair scheduling scheme in the TAS-SDPS can be formulated as

$$\{s, a\} = \arg \max_{m \in D, 1 \leq i \leq N_T} C_{s_m i d_m}.$$
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:

$$\{s, a\} = \arg \max_{m \in \Phi, 1 \leq i \leq N_T} \sum_{j=1}^{N_R} |h_{s_{mi}d_{mj}}|^2.$$

(13)

Therefore, the secrecy capacity of $S_k-D_k$ and $S_s-D_s$ in the TAS-SDPS scheme can be formulated as $C^s_{TAS} = (C_{s_kd_s} - C^s_{s_s})$ and $C^k_{TAS} = (C_{s_kd_s} - C^k_{s_s})$, respectively.

III. Secrecy Outage Analysis over Rayleigh Fading Channels

In this section, we present our performance analysis for the RSDPS, STC-SDPS and TAS-SDPS schemes for transmission over Rayleigh fading channels. The secrecy outage probability (SOP) expressions of the RSDPS scheduling as well as of the STC-SDPS and TAS-SDPS scheduling are derived.

A. 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 $D$ will be chosen to transmit with an equal probability. Therefore, according to the definition of SOP [7], we can obtain the SOP of the signal arriving from $S_m$ and $S_k$ in the first as well as second stage for the RSDPS scheme relying on the $S_m-D_m$ pair formulated as

$$P_{RSDPS}^{so_m_m} = \Pr \left( C_{s_m d_m} - C^m_{s_m e} < R_s \right),$$

(14)

and

$$P_{RSDPS}^{so_k_m} = \Pr \left( C_{s_m d_m} - C^k_{s_m e} < R_s \right),$$

(15)

respectively, where $R_s$ is a predefined secrecy rate. Upon combining (7), (9) and (10), we arrive at

$$P_{RSDPS}^{so_m_m} = \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_{mi}d_{mj}}|^2 < 2^{\frac{C_{s_m d_m}}{N_0}} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{s_{mi}e_l}|^2 + \Delta_0 \right)$$

(16)
and

\[ P_{RSDPS,so,k,m} = \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_{m,i},d_{m,j}}|^2 < \max \left( 2^{2R_s} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{s_{m,i},e_l}|^2, 2^{2R_s} \frac{N_E}{\Delta_1} \sum_{l=1}^{N_E} |h_{s_{m,i},e_l}|^2 \right) + \Delta_0 \right), \]  

(17)

respectively, where we have \( \Delta_0 = (2^{2R_s} - 1)N_TN_0/P_t \) and \( \Delta_1 = P_t/(P_sN_T) \). 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 \( \sigma^2_{md} = E(|h_{s_{m,i},d_{m,j}}|^2) \). 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 \( \sigma^2_{me} = E(|h_{s_{m,i},e_l}|^2) \), which is a common assumption widely used in the cooperative communication literature. Hence, according to (A.6) and (A.7), (16) and (17) can be obtained.

Hence, the SOP of the system investigated relying on \( S_m \) can be defined as

\[ P_{RSDPS,so,m} = \frac{1}{M} \left( \sum_{k \in D-\{i\}} (1 - P_{out,k,m}) P_{RSDPS,so,k,m} + P_{RSDPS,so,m,m} \right), \]  

(18)

where \( P_{out,k,m} = \Pr(C_{s_{k,s_{m}} < R_o}) = 1 - \exp(-\frac{R_o}{\sigma^2_{s_{k,s_{m}}}}) = a_{km} \), and \( R_o \) is the data rate of a pair of SNs links.

As mentioned above, in the RSDPS scheme, each SD pair has an equal probability to be chosen. Furthermore, using the law of total probability [29], we can obtain the SOP for the RSDPS scheme as

\[ P_{so}^{RSDPS} = \frac{1}{M} \sum_{m=1}^{M} P_{so,m}^{RSDPS}. \]  

(19)

**B. Proposed STC-SDPS Scheme**

Let us now analyze the SOP of the STC-SDPS scheme in this subsection. In the STC-SDPS scheme, an SD pair having the maximal channel capacity will be selected to participate in
transmitting the messages from the source to the destination. As discussed in (11), the index of the chosen pair associated with the STC-SDPS scheme is denoted by $s$. Hence, 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 shown to be

$$P_{so_s}^{STC} = \Pr \left( C_{s_s d_s} - C_{s_s e}^s < R_s \right)$$

and

$$P_{so_k}^{STC} = \Pr \left( C_{s_s d_s} - C_{s_s e}^k < R_s \right),$$

respectively.

Substituting $C_{s_s d_s}$ and $C_{s_s e}$ from (7), (9)-(10) into (20) and (21) yields

$$P_{so_s}^{STC} = \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_s d_j} \right|^2 < 2 \frac{2R_s}{B} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_s e_l} \right|^2 + \Delta_0 \right),$$

and

$$P_{so_k}^{STC} = \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_s d_j} \right|^2 < \max \left( 2 \frac{2R_s}{B} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_s e_l} \right|^2, \frac{2R_s}{B} \sum_{l=1}^{N_E} \left| h_{s_k e_l} \right|^2 \right) + \Delta_0 \right),$$

respectively.

In the spirit of [27], it is shown that performing the optimal user selection for the SD pairs can be viewed as being equivalent to the random pair selection for the E. Thus, using (11), both (22) and (23) can be expanded as

$$P_{so_s}^{STC} = \Pr \left( \max_{m \in D} \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_m d_j} \right|^2 < 2 \frac{2R_s}{B} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_m e_l} \right|^2 + \Delta_0 \right)$$

and

$$P_{so_k}^{STC} = \Pr \left( \max_{m \in D} \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_m d_j} \right|^2 < \max \left( 2 \frac{2R_s}{B} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_m e_l} \right|^2, \frac{2R_s}{B} \sum_{l=1}^{N_E} \left| h_{s_k e_l} \right|^2 \right) + \Delta_0 \right),$$

respectively.

Using (A.10) and (A.11), both (24) and (25) can be obtained. Similarly to (18), the SOP of
the STC-SDPS scheme may be formulated as

\[
P_{\text{so}}^{\text{STC}} = \frac{1}{M} \left( \sum_{k \in D - \{i\}} \left( 1 - P_{\text{out},k} \right) P_{\text{so},k}^{\text{STC}} + P_{\text{so},s}^{\text{STC}} \right),
\]

where \( P_{\text{out},k} \) is given by \( P_{\text{out},k} \), since for simplicity, we assume that the channel gains of each pair of SNs are independent and identically distributed (i.i.d).

C. Proposed TAS-SDPS Scheme

In this subsection, we present the SOP analysis of the TAS-SDPS scheme. As shown in (12), let \( s \) denote the index of the chosen antenna of an SD pair under the TAS-SDPS scheme. Thus, 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

\[
P_{\text{so}}^{\text{TAS}} = \Pr \left( C_{s_s} - C_{s_e} < R_s \right)
\]

and

\[
P_{\text{so}}^{\text{TAS}} = \Pr \left( C_{s_s} - C_{s_e} < R_s \right)
\]

respectively.

Using (8)-(10), both (27) and (28) can be rewritten as

\[
P_{\text{so}}^{\text{TAS}} = \Pr \left( \sum_{j=1}^{N_\text{E}} \left| h_{s_s d_s j} \right|^2 < 2 \frac{R_s}{B} \max \left( \sum_{l=1}^{N_\text{E}} \left| h_{s_s e_l} \right|^2 : \frac{1}{\Lambda_1} \sum_{l=1}^{N_\text{E}} \left| h_{s_k e_l} \right|^2 + \Lambda_0 \right) \right)
\]

and

\[
P_{\text{so}}^{\text{TAS}} = \Pr \left( \sum_{j=1}^{N_\text{E}} \left| h_{s_s d_s j} \right|^2 < 2 \frac{R_s}{B} \max \left( \sum_{l=1}^{N_\text{E}} \left| h_{s_s e_l} \right|^2 : \frac{1}{\Lambda_1} \sum_{l=1}^{N_\text{E}} \left| h_{s_k e_l} \right|^2 + \Lambda_0 \right) \right)
\]

respectively, where we have \( \Lambda_0 = (2 \frac{R_s}{B} - 1)N_0/P_t \), and \( \Lambda_1 = P_t/P_s \). Similarly to (24) and (25), based on (13), we arrive at:

\[
P_{\text{so}}^{\text{TAS}} = \Pr \left( \max_{m \in D, 1 \leq i \leq N_T} \sum_{j=1}^{N_\text{B}} \left| h_{s_m d_{o j}} \right|^2 < 2 \frac{R_s}{B} \sum_{l=1}^{N_\text{E}} \left| h_{s_m e_l} \right|^2 + \Lambda_0 \right)
\]
and

$$P_{so, k}^{\text{TAS}} = \Pr \left( \max_{m \in D, 1 \leq i \leq N_T} \sum_{j=1}^{N_R} |h_{sm_i, dj}|^2 < 2^{\frac{2R_s}{N}} \max \left( \sum_{i=1}^{N_E} |h_{sm_i, ei}|^2, \frac{1}{\Lambda_1} \sum_{i=1}^{N_E} |h_{sk_i, ei}|^2 + \Lambda_0 \right) \right), \quad (32)$$

respectively.

Finally, using (A.17) and (A.18), both (31) and (32) can be obtained. Moreover, relying on the definition in (18), the SOP of the investigated system relying on the proposed TAS-SDPS scheme can be expressed as:

$$P_{so}^{\text{TAS}} = \frac{1}{M} \left( \sum_{k \in D \setminus \{i\}} (1 - P_{out, k}^{\text{TAS}}) P_{so, k}^{\text{TAS}} + P_{so, k}^{\text{TAS}} \right). \quad (33)$$

IV. SECRECY DIVERSITY GAIN ANALYSIS

In this section, we present the secrecy diversity analysis of the RSDPS, STC-SDPS, and TAS-SDPS schemes in the high MER region for the sake of providing further insights from (16), (17), (24), (25), (31) and (32) conceiving both the conventional RSDPS as well as the proposed STC-SDPS and TAS-SDPS schemes.

A. Traditional RSDPS Scheme

This subsection analyzes the asymptotic SOP of the conventional RSDPS scheme. In the spirit of [28], the traditional diversity gain is defined as

$$d = - \lim_{SNR \to \infty} \frac{\log P_e (SNR)}{\log SNR}, \quad (34)$$

which is used for characterizing the reliability of wireless communications, where $SNR$ and $P_e (SNR)$ 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, STC-SDPS, 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), (25), (31) and (32), the SOP of the RSDPS scheme is related to the main channel $|h_{sm_i, dm_j}|^2$ as
well as to the eavesdropping channels $|h_{s_m,e_i}|^2$ and $|h_{s_k,e_l}|^2$. For notational convenience again, let $\lambda_{se} = \sigma^2_{md}/\sigma^2_{me}$ denote the MER. In spirit of the above observation, we define the secrecy diversity gain as the asymptotic ratio of the logarithmic SOP to the logarithmic MER $\lambda_{se}$ as $\lambda_{se} \to \infty$, which is mathematically formulated as

$$d = - \lim_{\lambda_{se} \to \infty} \frac{\log(P_{so})}{\log(\lambda_{se})}. \quad (35)$$

Meanwhile, in (35), the SOP $P_{so}$ behaves as $\lambda_{se}^{-d}$ in the high MER region, which means that upon increasing the diversity gain $d$, $P_{so}$ decreases faster in the high MER region.

Using (35), the secrecy diversity gain of the RSDPS scheme can be expressed as

$$d_{RSDPS} = - \lim_{\lambda_{se} \to \infty} \frac{\log(P_{RSDPS}^{so})}{\log(\lambda_{se})}. \quad (36)$$

Moreover, using the inequality $\sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_m,d_m}|^2 \leq N_T N_R \max_{i,j} |h_{s_m,d_m}|^2$, $2 \frac{2R}{\beta} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{s_m,e_l}|^2 + \Delta_0 \geq 2 \frac{2R}{\beta} \max_{i,l} |h_{s_m,e_l}|^2$, and $\frac{1}{\Delta_1} \max_{i,l} |h_{s_k,e_l}|^2$ into (16), we have

$$P_{so}^{RSDPS} \geq \frac{1}{M} \sum_{m=1}^{M} \frac{1}{M} \left( \Pr \left( N_T N_R \max_{i,j} |h_{s_m,d_m}|^2 < \frac{2R}{\beta} \max_{i,l} |h_{s_m,e_l}|^2 \right) \right.$$

$$\left. + \sum_{k \in D \setminus \{i\}} a_{km} \Pr \left( N_T N_R \max_{i,j} |h_{s_m,d_m}|^2 < \frac{2R}{\beta} \max_{i,l} \left( \max_{i,l} |h_{s_m,e_l}|^2 + \frac{1}{\Delta_1} \max_{i,l} |h_{s_k,e_l}|^2 \right) \right) \right). \quad (37)$$

Based on (B.12) and (B.13), (37) can be reformulated as (38) shown at the top of the following page.

Combining (36) and (38) yields

$$d_{RSDPS} \leq N_T N_R. \quad (39)$$
\[ p_{RSDPS} \leq \frac{1}{M} \sum_{m=1}^{M} \left( \sum_{n=1}^{N_T N_R} (-1)^{C_{n}^{m}} \omega_{n} + \sum_{g=1}^{2} \sum_{t=0}^{2} (-1)^{C_{n}^{t} g} \phi \alpha_{kg} \beta_{dt} + \sum_{n=1}^{2} \sum_{g=1}^{2} \sum_{t=0}^{2} (-1)^{C_{n}^{t} g} \phi \alpha_{kg} \beta_{dt} \right) \left( \frac{1}{\lambda_{ac}} \right)^{N_T N_R}. \] (41)

Furthermore, in the high-SNR region we can observe from (17) that as the transmit power \( P_t \) tends to infinity, \( \Delta_0 \) approaches zero. Substituting the inequality \( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{sm}(d_{mj})|^2 \geq \max_{i,j} |h_{sm}(d_{mj})|^2 \),
\[ 2^{2R_s} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{sm,el}|^2 + \Delta_0 \leq 2^{2R_s} N_T N_E \max_{i,l} |h_{sm,el}|^2, \]
and \( 2^{2R_s} \max_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{sm,el}|^2, \)
\[ \Delta_0 \leq 2^{2R_s} \max_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{sm,el}|^2, \]
into (18) yields
\[ P_{RSDPS} \leq \frac{1}{M} \sum_{m=1}^{M} \left( \Pr \left( \max_{i,j} |h_{sm}(d_{mj})|^2 < 2^{2R_s} N_T N_E \max_{i,l} |h_{sm,el}|^2 \right) \right) + \sum_{k \in D-\{i\}} \alpha_{km} \Pr \left( \max_{i,j} |h_{sm}(d_{mj})|^2 < 2^{2R_s} \max_{i,l} \left( N_T N_E \max_{i,l} |h_{sm,el}|^2 + \frac{N_E}{\Delta_1} \max_{i,l} |h_{sk,el}|^2 \right) \right). \] (40)

Similarly to (37), (40) can be reformulated as (41) shown at the top of the following page, where \( \omega_{n} = (N_T N_R)! \left( N_T N_E \right)^{N_T N_R} \left( \sum_{i,j} \frac{1}{\alpha_{sm,el}^{i,j}} \right)^{N_T N_R} \left( \prod_{i,j} \alpha_{sm,el}^{i,j} \right)^{-1}, \)
\[ \alpha_{i,j} = \frac{\sum_{i,j} \frac{1}{\alpha_{sm,el}^{i,j}}}{\left( N_T N_R \right)! \left( N_T \Delta_1 \right)^{N_T N_R}} \left( \sum_{i,j} \frac{1}{\alpha_{sm,el}^{i,j}} \right)^{-1}, \]
\[ \beta_{dt} = \frac{\sum_{i,j} \frac{1}{\alpha_{sm,el}^{i,j}}}{\left( N_T N_R - \delta \right)! \left( N_T \Delta_1 \right)^{N_T N_R}} \left( \sum_{i,j} \frac{1}{\alpha_{sm,el}^{i,j}} \right)^{-1}. \]

Moreover, substituting (41) into (36) yields
\[ d_{RSDPS} \geq N_T N_R. \] (42)

Therefore, based on (39) and (42), the secrecy diversity gain of the conventional RSDPS scheme can be expressed as
\[ d_{RSDPS} = N_T N_R, \] (43)
which shows that the RSDPS scheme only attains a secrecy diversity gain of \( N_T N_R \), and results in the SOP of the RSDPS scheme behaving as \( \left( \frac{1}{\lambda_{ac}} \right)^{N_T N_R} \) in the high-MER region.
B. Proposed STC-SDPS Scheme

This subsection presents the secrecy diversity gain analysis of the STC-SDPS scheme. Similar to (36), the secrecy diversity order of the STC-SDPS scheme is defined as

\[
d_{\text{STC}} = - \lim_{\lambda_{se} \to \infty} \frac{\log (P_{\text{so}^\text{STC}})}{\log (\lambda_{se})}. \tag{44}
\]

Based on the inequality

\[
\max_{m} \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_m,d_{m,j}}|^2 \leq N_T N_R \max_{m,i,j} |h_{s_m,d_{m,j}}|^2 + 2^\frac{2R_s}{N_T} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{s_{m,l}}|^2 + \Delta_0 \geq 2^\frac{2R_s}{N_T} \max_{i,l} |h_{s_{m,l}}|^2,
\]

\[
\Delta_0 \geq 2^\frac{2R_s}{N_T} \max_{i,l} |h_{s_{m,l}}|^2 \text{, and } 2^\frac{2R_s}{N_T} \max_{i,l} |h_{s_{m,l}}|^2 + \frac{1}{\Delta_1} \max_{i,l} |h_{s_{m,l}}|^2 \text{, a lower bound on the SOP of the STC-SDPS scheme can be calculated as}
\]

\[
P_{\text{so}^\text{STC}} \geq \frac{1}{M} \left( \Pr \left( N_T N_R \max_{m,i,j} |h_{s_m,d_{m,j}}|^2 < 2^\frac{2R_s}{N_T} \max_{i,l} |h_{s_{m,l}}|^2 \right) \right)
\]

\[
+ \sum_{k \in D^\prime} a_{km} \Pr \left( N_T N_R \max_{m,i,j} |h_{s_m,d_{m,j}}|^2 < 2^\frac{2R_s}{N_T} \max \left( \max_{i,l} |h_{s_{m,l}}|^2 + \frac{1}{\Delta_1} \max_{i,l} |h_{s_{m,l}}|^2 \right) \right). \tag{45}
\]

From (B.14) and (B.15), we arrive at (46) shown at the top of the following page.

\[
d_{\text{STC}} \leq M N_T N_R. \tag{47}
\]

Furthermore, utilizing the inequality

\[
\max_{m} \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_m,d_{m,j}}|^2 \geq \max_{m,i,j} |h_{s_m,d_{m,j}}|^2 + 2^\frac{2R_s}{N_T} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} |h_{s_{m,l}}|^2 + \Delta_0 \leq 2^\frac{2R_s}{N_T} N_T N_E \max_{i,l} |h_{s_{m,l}}|^2 \text{, and } 2^\frac{2R_s}{N_T} \max_{i,l} |h_{s_{m,l}}|^2 + \frac{1}{\Delta_1} \sum_{l=1}^{N_E} |h_{s_{m,l}}|^2\]

\[
\Delta_0 \leq 2^\frac{2R_s}{N_T} N_T N_E \max_{i,l} |h_{s_{m,l}}|^2 \text{, and } 2^\frac{2R_s}{N_T} \max_{i,l} |h_{s_{m,l}}|^2 + \frac{1}{\Delta_1} \max_{i,l} |h_{s_{m,l}}|^2 \text{, we can formulate an upper bound on the SOP of the}
\]

\[
\]

\[
(46)
\]

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proposed STC-SDPS scheme as

\[
P_{\text{STC}}^{\text{so}} \leq \frac{1}{M} \left( \sum_{n=1}^{2N_E-1} (-1)^n |C_n| \omega_{\text{mil}}^{1} + \sum_{n=1}^{2N_E-1} \sum_{t=0}^{M_N T N_R} (-1)^n |C_n| a_{km} \omega_{\text{mil}}^{1} + \sum_{n=1}^{2N_E-1} \sum_{t=0}^{M_N T N_R} (-1)^n |C_n| a_{km} \omega_{\text{mil}}^{1} \right) \left( \frac{1}{\lambda_{\text{se}}} \right)^{M_N T N_R}. \tag{49}\]

Similarly to (45), (48) can be reformulated as (49) shown at the top of the following page, where

\[
\alpha_{\text{mil}}^{1} = \left( \frac{(MN_T N_R-1)!}{(MN_T N_R-1)! N_T \Delta_1} \{ \sum_{l \in F_g} 1 \} \prod_{m,i,j} \alpha_{s_{m_{i_{j}}}} \right)^{1+1}, \quad \omega_{\text{mil}}^{1} = \left( MN_T N_R \right)^{1} \left( \frac{2^{R_b}}{N_T N_E} \right)^{M_N T N_R} \left( \sum_{l \in F_g} 1 \right)^{1+1}. \]

Using (44) and (49), we arrive at

\[
d_{\text{STC}} \geq MN_T N_R. \tag{50}\]

Hence, the secrecy diversity gain of the proposed STC-SDPS scheme can be expressed as

\[
d_{\text{STC}} = MN_T N_R. \tag{51}\]

It can be observed from (51) that the proposed STC-SDPS scheme achieves the secrecy diversity gain of $MN_T N_R$, which means that the SOP of the STC-SDPS scheme behaves as $(\frac{1}{\lambda_{\text{se}}})^{MN_T N_R}$ in the high-MER region. Therefore, the STC-SDPS scheme advocated significantly outperforms the conventional RSDPS scheme in terms of its SOP.
C. Proposed TAS-SDPS Scheme

This subsection is focused on the secrecy diversity analysis of the TAS-SDPS scheme. Similarly to (36), the secrecy diversity order of the TAS-SDPS scheme can be expressed as

$$d_{\text{TAS}} = -\lim_{\lambda \to \infty} \frac{\log (P_{\text{so}}^{\text{TAS}})}{\log (\lambda)}.$$  \hfill (52)

Thus, let us analyze the secrecy diversity analysis of the TAS-SDPS scheme. Considering the inequality

$$\max_{m \in D, 1 \leq j \leq N_T} \sum_{l=1}^{N_E} |h_{s_{ml}d_{mj}}|^2 \leq N_r \max_{m, i, j} |h_{s_{ml}d_{mj}}|^2, \quad 2^{\frac{2R_s}{N_r}} \max_{l=1}^{N_E} |h_{s_{ml}e_l}|^2 + \Lambda_0 \geq 2^{\frac{2R_s}{N_r}} \max_{l} |h_{s_{ml}e_l}|^2,$$

and

$$2^{\frac{2R_s}{N_r}} \max_{l} (\sum_{l=1}^{N_E} |h_{s_{ml}e_l}|^2, \frac{1}{\Lambda_1} \sum_{l=1}^{N_E} |h_{s_{ml}e_l}|^2),$$

we arrive at

$$P_{\text{so}}^{\text{TAS}} \geq \frac{1}{M} \left( \Pr \left( N_r \max_{m, i, j} |h_{s_{ml}d_{mj}}|^2 < 2^{\frac{2R_s}{N_r}} \max_{l} |h_{s_{ml}e_l}|^2 \right) \right) + \frac{\alpha_{\text{mil}2}}{\alpha_{\text{mil}2} + \sum_{k \in D - \{i\}} \alpha_{km}} \left( \Pr \left( N_r \max_{m, i, j} |h_{s_{ml}d_{mj}}|^2 < 2^{\frac{2R_s}{N_r}} \max_{l} |h_{s_{ml}e_l}|^2 \right) \right).$$  \hfill (53)

With the aid of (B.14) and (B.15), we arrive at (54) shown at the top of the following page, where

$$\alpha'_{d2} = \frac{\alpha_{d2}}{\alpha_{d2} + \sum_{l \in E_n \setminus A'} \alpha_{km}} + \sum_{l \in E_n \setminus A'} \frac{1}{\alpha_{km}}, \quad \omega_{\text{mil}2} = (M N_T N_R) ! (\frac{2R_s}{N_r}) \left( \prod_{i \in C_n} \frac{1}{\alpha_{km}} \right) X_{s_{ml}d_{mj}}^{-1}, \quad \alpha_{\text{mil}2} = \frac{(M N_T N_R) ! (\sum_{l \in E_n \setminus A'} \alpha_{km})^M N_T N_R - (M N_T N_R - 1)^{t(\alpha'_{d2})} + 1}{(M N_T N_R - 1)^{(\sum_{l \in E_n \setminus A'} \alpha_{km})^M N_T N_R - t(\alpha'_{d2})}}$$

and

$$\beta_{\text{mil}2} = \frac{(M N_T N_R - 1)^{(\sum_{l \in E_n \setminus A'} \alpha_{km})^M N_T N_R - t(\alpha'_{d2}) - 1}}{(M N_T N_R - 1)^{t(\sum_{l \in E_n \setminus A'} \alpha_{km})^M N_T N_R - (M N_T N_R - t(\alpha'_{d2}) + 1)}}.$$

Substituting (54) into (52) yields

$$d_{\text{TAS}} \leq M N_T N_R.$$  \hfill (55)

Furthermore, upon considering an infinite SNR and using the inequality

$$\max_{m, i, j} |h_{s_{ml}d_{mj}}|^2, \quad 2^{\frac{2R_s}{N_r}} \sum_{l=1}^{N_E} |h_{s_{ml}e_l}|^2 + \Lambda_0 \leq 2^{\frac{2R_s}{N_r}} N_r \max_{l} |h_{s_{ml}e_l}|^2, \quad \text{and} \quad 2^{\frac{2R_s}{N_r}} \max_{l} (\sum_{l=1}^{N_E} |h_{s_{ml}e_l}|^2, \frac{1}{\Lambda_1} \sum_{l=1}^{N_E} |h_{s_{ml}e_l}|^2),$$

the secrecy diversity order becomes

$$d_{\text{TAS}} \leq M N_T N_R.$$  \hfill (55)
Specifically, the analytic SOPs of the RSDPS, STC-SDPS and TAS-SDPS schemes are evaluated in terms of their SOPs and secrecy diversity gains. By combining (55) and (58), we arrive at the secrecy diversity gain of the proposed TAS-SDPS scheme as

\[ d_{\text{TAS}} \geq MN_T N_R. \]  (58)

By combining (55) and (58), we arrive at the secrecy diversity gain of the proposed TAS-SDPS scheme as

\[ d_{\text{TAS}} = MN_T N_R. \]  (59)

Therefore, we can see from (51) and (59) that the TAS-SDPS scheme can attain the same secrecy diversity gain as the STC-SDPS scheme both in terms of the instantaneous channel capacity and the antenna selection.

V. PERFORMANCE EVALUATION

In this section, we present our performance comparisons among the RSDPS, the proposed TAS-SDPS and the STC-SDPS schemes in terms of their SOPs and secrecy diversity gains. Specifically, the analytic SOPs of the RSDPS, STC-SDPS and TAS-SDPS schemes are evaluated...
by plotting (19), (26) and (33), respectively. Moreover, the lower bound SOPs of the RSDPS, STC-SDPS and TAS-SDPS schemes are obtained by using (38), (46) and (54), respectively. The upper bound SOP of the RSDPS, STC-SDPS and TAS-SDPS schemes are obtained by using (41), (49) and (57), respectively. The simulated SOP of the RSDPS as well as the proposed STC-SDPS and the TAS-SDPS schemes are also provided for demonstrating the correctness of the theoretical results. In our numerical evaluation, we assume that $\alpha_{s_m e_l} = \alpha_{s_k e_l} = \alpha_{s_m d_m} = 1$. For comparison, the traditional non-cooperative (Non-coop) transmission scheme is also presented, wherein the heterogeneous transmission pairs work independently, and each pair occupies the $\frac{B}{M}$ Hz channel bandwidth. For the sake of a secrecy rate comparison with the cooperative schemes, the secrecy rate of the Non-coop scheme is $R_{s M}$. Hence, the SOP of the Non-coop scheme is expressed as

$$P_{so}^{Non} = \sum_{m=1}^{M} \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} |h_{s_m d_m}|^2 < 2 \frac{B}{M} \sum_{i=1}^{N_T} \sum_{j=1}^{N_E} |h_{s_m e_l}|^2 + \Delta'_0 \right),$$  

where $\Delta'_0 = (2^{\frac{B}{M}} - 1) N_T N_0 / P_t$, and $P_{so}^{Non}$ can be obtained similarly to (16).

![Fig. 3. SOP vs MER $\lambda_{se}$ of the traditional RSDPS and Fig. 4. SOP vs SNR $\frac{P_t}{N_0}$ of the traditional RSDPS and Non-Non-coop as well as of the proposed STC-SDPS and TAS-SDPS coop as well as of the proposed STC-SDPS and TAS-SDPS schemes for different (NT, NR, NE) with M = 4, which were schemes for different MER with NT = NR = NE = 2, and calculated from (19), (60), (26), and (33).](image)

![Fig. 4. SOP vs SNR $\lambda_{se}$ of the traditional RSDPS and Fig. 4. SOP vs SNR $\frac{P_t}{N_0}$ of the traditional RSDPS and Non-Non-coop as well as of the proposed STC-SDPS and TAS-SDPS coop as well as of the proposed STC-SDPS and TAS-SDPS schemes for different (NT, NR, NE) with M = 8, which were calculated from (19), (60), (26), and (33).](image)

In Fig. 3, we show the SOP versus MER $\lambda_{se}$ of both the traditional RSDPS and of the Non-coop as well as of the proposed TAS-SDPS and STC-SDPS schemes for different pa-
The number of SD pairs $M$ of the traditional RSDPS and Non-coop as well as the proposed traditional RSDPS as well as the proposed STC-SDPS and STC-SDPS and TAS-SDPS schemes for different $N_E$ with TAS-SDPS schemes with $N_T = N_R = N_E = 2$, and $M = 4$, $N_T = N_R = 2$, and $\lambda_{se} = 10$dB, which were calculated from which were calculated from (38), (46), (54), (19), (26), (33), (19), (60), (26), and (33).

Fig. 5. SOP vs. the number of source-destination pairs $M$ of Fig. 6. Asymptotic and exact results on the SOP of the traditional RSDPS as well as the proposed STC-SDPS and TAS-SDPS schemes with $N_T = N_R = N_E = 2$, and $M = 4$, (38), (46), (54), (19), (26), (33), (41), (49) and (57).

It is shown in Fig. 3 that the SOPs of the RSDPS, of the Non-coop, of the TAS-SDPS and of the STC-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, the TAS-SDPS and the STC-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. 3 also demonstrates that increasing the MER upgrades the security of wireless transmissions in heterogeneous networks. Additionally, Fig. 3 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 and STC-SDPS schemes, when the MER increases from -10dB to 10dB.

Fig. 4 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 and STC-SDPS schemes. Fig. 4 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 and STC-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. 4 that the SOPs of the proposed TAS-SDPS and STC-SDPS schemes are lower than those 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 and STC-SDPS schemes.

Fig. 5 shows our SOP comparison of the traditional RSDPS and Non-coop as well as of the proposed STC-SDPS and TAS-SDPS schemes for different number of the SD pairs $M$. Observe from Fig. 5 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 reduced significantly, which shows that increasing the number of SD pairs is beneficial for the physical-layer security of the proposed 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 physical-layer security of heterogeneous 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 an 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. 5, the proposed TAS-SDPS and STC-SDPS schemes outperform the Non-coop and RSDPS schemes in terms of their SOPs for all the $M$ values.

Fig. 6 shows both the asymptotic and the exact results conceiving the SOP of the traditional RSDPS as well as of the proposed STC-SDPS and TAS-SDPS schemes, where the lower bound results, exact results and the upper bound results are obtained by plotting (38), (46), (54), (19), (26), (33), (41), (49) and (57) as a function of the MER, respectively. Observe from Fig. 6 that
Table 2 Performance metrics of the RSDPS, STC-SDPS, and TAS-SDPS schemes

| Schemes   | Secrecy Outage Probability | Secrecy Diversity Gain |
|-----------|----------------------------|------------------------|
| RSDPS     | (19)                       | (43)                   |
| STC-SDPS  | (26)                       | (51)                   |
| TAS-SDPS  | (33)                       | (59)                   |

the exact SOP curves of the RSDPS, the TAS-SDPS and STC-SDPS schemes are more and more close to their corresponding lower and upper bounds, as the MER increases. Moreover, as shown in Fig. 6, in the high-MER region, the exact SOP curves of the RSDPS, TAS-SDPS and STC-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, TAS-SDPS and STC-SDPS schemes in the high-MER region.

VI. CONCLUSIONS

In this paper, we explored a heterogeneous wireless network coexisting with multiple wireless systems in the face of an eavesdropper, supporting multiple SD pairs, where each SD pair may access the shared spectrum dynamically, and the eavesdropper aims for maliciously wiretapping the signals transmitted by the user nodes relying on a wide-band receiver. We proposed a heterogeneous cooperative framework relying on two stages for enhancing the physical-layer security of the ongoing wireless transmissions, wherein an SD pair will be chosen as the transmitting pair within a given spectral band from the perspective of security. Moreover, we presented two SD pair scheduling schemes, which are termed as the TAS-SDPS and STC-SDPS, respectively. We analyzed the SOPs of the proposed TAS-SDPS and STC-SDPS schemes, 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 and STC-SDPS schemes, as well as of the RSDPS scheme, and both the SOP and the secrecy diversity gain of the RSDPS, TAS-SDPS and STC-DSPS schemes are summarized in table 2. It was demonstrated that the
TAS-SDPS scheme outperforms both the STC-SDPS, as well as the RSDPS and the Non-coop schemes in terms of their SOPs, whilst the STC-SDPS achieves the same secrecy diversity gain as that of the TAS-SDPS. Furthermore, as the number of SD pairs increases, the SOPs of the TAS-SDPS and STC-SDPS schemes improve, while the SOPs of the RSDPS and Non-coop schemes remain unchanged.

**APPENDIX A**

Upon defining $U = \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_{m_i}d_{m_j}} \right|^2$, $X_1 = \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_{m_i}e_l} \right|^2$, and $X_2 = \sum_{l=1}^{N_E} \left| h_{s_k e_l} \right|^2$, and taking into account that the RVs $\left| h_{s_{m_i}d_{m_j}} \right|^2$, $\left| h_{s_k e_l} \right|^2$, and $\left| h_{s_{m_i}e_l} \right|^2$ are independent of each other, $P_{\text{RSDPS}_{so_{m, m}}}$ and $P_{\text{RSDPS}_{so_{k, m}}}$ can be expressed as

$$P_{\text{RSDPS}_{so_{m, m}}} = \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_{m_i}d_{m_j}} \right|^2 < 2^{\frac{2R_s}{\sigma^2}} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_{m_i}e_l} \right|^2 + \Delta_0 \right)$$

$$= \int_0^\infty F_U \left( \Delta_0 + 2^{\frac{2R_s}{\sigma^2}} x_1 \right) f_{X_1} (x_1) \, dx_1 \tag{A.1}$$

and

$$P_{\text{RSDPS}_{so_{k, m}}} = \Pr \left( \sum_{i=1}^{N_T} \sum_{j=1}^{N_R} \left| h_{s_{m_i}d_{m_j}} \right|^2 < \max \left( 2^{\frac{2R_s}{\sigma^2}} \sum_{i=1}^{N_T} \sum_{l=1}^{N_E} \left| h_{s_{m_i}e_l} \right|^2, 2^{\frac{2R_s}{\sigma^2}} \sum_{j=1}^{N_E} \left| h_{s_k e_l} \right|^2 + \Delta_0 \right) \right)$$

$$= \int_0^\infty \int_{\frac{\Delta_1 x_1}{x_1}}^\infty F_U \left( \Delta_0 + 2^{\frac{2R_s}{\sigma^2}} x_1 \right) f_{X_1} (x_1) f_{X_2} (x_2) \, dx_1 \, dx_2$$

$$+ \int_0^\infty \int_{\frac{\Delta_1 x_2}{x_2}}^\infty F_U \left( \Delta_0 + 2^{\frac{2R_s}{\sigma^2}} x_2 \right) f_{X_2} (x_2) f_{X_1} (x_1) \, dx_2 \, dx_1, \tag{A.2}$$

respectively, where $F_U(u)$ is the cumulative distribution function (CDF) of RV $U$, and $f_{X_1}(x_1)$ and $f_{X_2}(x_2)$ are the probability density functions (PDFs) of the RVs $X_1$ and $X_2$, respectively.

Based on [8], they can be expressed as:

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

and

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

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

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

\[
P_{s_{o_{m_m}}}^{RSDPS} = \int_0^{\infty} F_U \left( \Delta_0 + 2^{\frac{2B_s}{T}} x_1 \right) f_{X_1}(x_1) \, dx_1 
= \left[ 1 - \sum_{l=0}^{N_T N_{E-1}} \sum_{p=0}^{N_T N_{E-1}} \frac{(p + N_T N_{E-1})!}{(p-l)! (N_T N_{E-1})!} \left( \frac{2^{\frac{2B_s}{T}}}{\sigma_{md}^2} \right)^{l} \left( \frac{1}{\sigma_{me}^2} \right)^{N_T N_{E-1}} (l-p) \left( \frac{1}{\sigma_{me}^2} \right)^{l-p} \left( \frac{2^{\frac{2B_s}{T}}}{\sigma_{md}^2} \right)^{-p} e^{-\frac{\Delta_0}{\sigma_{md}^2}} \right], \tag{A.6} \]

Furthermore, substituting (A.3)-(A.5) into (A.2) yields

\[
P_{s_{o_{k_m}}}^{RSDPS} = \sum_{l=0}^{N_T N_{E-1}} \frac{\left( \frac{1}{\Delta_{k_e}^2} \right)^l}{l! \left( \frac{1}{\sigma_{me}^2} \Delta_{k_e}^2 \right)^{l}} \sum_{p=0}^{N_T N_{E-1}} \frac{(p + N_T N_{E-1})!}{(p-l)! (N_T N_{E-1})!} \left( \frac{2^{\frac{2B_s}{T}}}{\sigma_{md}^2} \right)^{l} \left( \frac{1}{\sigma_{me}^2} \right)^{N_T N_{E-1}} (l-p) \left( \frac{1}{\sigma_{me}^2} \right)^{l-p} \left( \frac{2^{\frac{2B_s}{T}}}{\sigma_{md}^2} \right)^{-p} e^{-\frac{\Delta_0}{\sigma_{md}^2}}, \tag{A.7} \]

where \( \alpha_{tp} = \frac{(\frac{1}{\sigma_{k_e}^2})^{N_T N_{E-1}} (\frac{1}{\sigma_{me}^2})^{N_T N_{E-1}} \left( \frac{2^{\frac{2B_s}{T}}}{\sigma_{md}^2} \right)^{-\Delta_0}}{p!(l-p)! (N_T N_{E-1})!(N_T N_{E-1})!} \), \( \alpha_{cmd} = \frac{(\frac{1}{\sigma_{me}^2})^{N_T N_{E-1}} \left( \frac{2^{\frac{2B_s}{T}}}{\sigma_{md}^2} \right)^{-\Delta_0}}{p!(l-p)! (N_T N_{E-1})!(N_T N_{E-1})!} \), \( \alpha_{km} = \frac{1}{\sigma_{k_e}^2} + \frac{1}{\Delta_{k_e} \sigma_{me}^2} \), and \( \alpha_{km} = \frac{1}{\Delta_{k_e} \sigma_{me}^2} \).

Similarly, \( P_{s_{o_{s_k}}}^{STC} \) and \( P_{s_{o_{k_s}}}^{STC} \) can be rewritten as

\[
P_{s_{o_{s_k}}}^{STC} = \Pr \left( \max_{m \in D} \sum_{i=1}^{N_T} \sum_{j=1}^{N_{E}} |h_{s_{m_i} m_j}|^2 < 2^{\frac{2B_s}{T}} \sum_{i=1}^{N_T} \sum_{l=1}^{N_{E}} |h_{s_{m_i} e_l}|^2 + \Delta_0 \right)
= \int_0^{\infty} \prod_{m \in D} F_U \left( \Delta_0 + 2^{\frac{2B_s}{T}} x_1 \right) f_{X_1}(x_1) \, dx_1 \tag{A.8} \]

and

\[
P_{s_{o_{k_s}}}^{STC} = \Pr \left( \max_{m \in D} \sum_{i=1}^{N_T} \sum_{j=1}^{N_{E}} |h_{s_{m_i} m_j}|^2 \leq \max \left( 2^{\frac{2B_s}{T}} \sum_{i=1}^{N_T} \sum_{l=1}^{N_{E}} |h_{s_{m_i} e_l}|^2, \frac{2^{\frac{2B_s}{T}} N_{E}}{\Delta_1} \sum_{l=1}^{N_{E}} |h_{s_{e_l} e_l}|^2 \right) + \Delta_0 \right)
= \int_0^{\infty} \int_0^{\infty} \prod_{m \in D} F_U \left( \Delta_0 + 2^{\frac{2B_s}{T}} x_1 \right) f_{X_1}(x_1) f_{X_2}(x_2) \, dx_1 \, dx_2 
+ \int_0^{\infty} \int_0^{\infty} \prod_{m \in D} F_U \left( \Delta_0 + 2^{\frac{2B_s}{T}} x_2 \right) f_{X_1}(x_1) f_{X_2}(x_2) \, dx_1 \, dx_2 \tag{A.9} \]

respectively.
Relying on [9], substituting (A.3) and (A.4) into (A.8) yields

\[
P_{\text{so,k}}^{\text{STC}} = \int_0^\infty \prod_{m \in D} F_U \left( \Delta_0 + 2 \frac{2R_s}{BR} v \right) f_V(v) \, dv
\]
\[
= \sum \sum_{S} \sum_{p=0}^{\alpha_2} \int_0^\infty \Phi_0 v^{p + N_T N_E - 1} \exp \left( - \frac{v}{\sigma^2_{\text{me}}} - \alpha_3 \frac{2 R_s}{BR} v \right) \, dv
\]
\[
= \sum \sum_{S} \sum_{p=0}^{\alpha_2} \Phi_0 (p + N_T N_E - 1)! \left( \frac{1}{\sigma^2_{\text{me}}} + \alpha_3 \frac{2 R_s}{BR} \right)^{-p - N_T N_E}
\]

where \( \alpha_1 = \frac{|D|}{N_T N_E - 1} \prod_{j=1}^{N_T N_E} \left( \sigma^2_{\text{me}} \right)^{j-1} \), \( \alpha_2 = \sum_{j=1}^{N_T N_E} \), \( \alpha_3 = \frac{1}{\sigma^2_{\text{me}}} |D| - n_{N_T N_E + 1} \)

Furthermore, upon using (A.3)-(A.5), we arrive at

\[
P_{\text{so,k}}^{\text{TAS}} = \sum \sum_{S} \sum_{p=0}^{\alpha_2} \sum_{t=0}^{N_T N_E - 1} \alpha_{op} c_{pd} \left( \frac{d_{km}}{\Delta_1 + \alpha_3 \frac{2 R_s}{BR}} \right)^{-N_T N_E - t} \sum \sum_{S} \sum_{p=0}^{\alpha_2} \sum_{t=0}^{N_T N_E - 1} \alpha_{op} d_{pd} \left( \frac{c_{km} \Delta_1 + \alpha_3 \frac{2 R_s}{BR}}{\Delta_1} \right)^{-t - N_T N_E - t},
\]

where \( \alpha_{op} = \frac{(1/2)^{N_E} (1/\sigma^2_{\text{me}})^{N_T N_E} (2 R_s)^{p (\Delta_0) \alpha_3 - p (\alpha_2) \alpha_1 \Delta_0}}{1/\sigma^2_{\text{me}} + 2 \frac{2 R_s}{BR} \alpha_3}, \)

\( c_{pd} = \frac{(1/\sigma^2_{\text{me}} + 2 \frac{2 R_s}{BR} \alpha_3)^{p - N_T N_E + t \Delta_1^{-t} \Delta_1^{-t+1}}}{(p + N_T N_E - 1)!} \), and \( d_{pd} = \frac{(1/\sigma^2_{\text{me}} + 2 \frac{2 R_s}{BR} \alpha_3)^{p - N_T N_E + t \Delta_1^{-t} \Delta_1^{-t+1}}}{(p + N_T N_E - 1)!} \).

Moreover, defining \( Q = \sum_{j=1}^{N_T} |h_{s_m, d_m}|^2 \), \( W_1 = \sum_{l=1}^{N_E} |h_{s_m, e_l}|^2 \), 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, \( P_{\text{so,k}}^{\text{TAS}} \) and \( P_{\text{so,k}}^{\text{TAS}} \) can be formulated as

\[
P_{\text{so,k}}^{\text{TAS}} = \operatorname{Pr} \left( \max_{m \in D, 1 \leq l \leq N_T} \sum_{j=1}^{N_T} \left| h_{s_m, d_m} \right|^2 < 2 \frac{2 R_s}{BR} \sum_{l=1}^{N_E} \left| h_{s_m, e_l} \right|^2 + \Lambda_0 \right)
\]
\[
= \int_0^\infty \prod_{m \in D, 1 \leq l \leq N_T} F_Q \left( \Lambda_0 + 2 \frac{2 R_s}{BR} w_1 \right) f_{W_1}(w_1) \, dw_1
\]
where \( \beta \) respectively. Substituting (A.14) and (A.15) into (A.12) yields

\[
P_{so,k}^{TAS} = \Pr \left( \max_{m \in D, 1 \leq i \leq N_T} \left| h_{s_m,d_n} \right|^2 < \max \left( \frac{2^{2R_s}}{H} \sum_{l=1}^{N_R} \left| h_{s_{m,l}} \right|^2 \right) + \Lambda_0 \right)
\]

\[
= \int_0^\infty \int_0^\infty \prod_{m \in D, 1 \leq i \leq N_T} F_Q \left( \Lambda_0 + \frac{2^{2R_s}}{H} w_1 \right) f_{W_1}(w_1) f_{W_2}(w_2) \, dw_1 \, dw_2
\]

\[
+ \int_0^\infty \int_{\Lambda_1 w_1}^\infty \prod_{m \in D, 1 \leq i \leq N_T} F_Q \left( \Lambda_0 + \frac{2^{2R_s}}{H} w_2 \right) f_{W_2}(w_2) f_{W_1}(w_1) \, dw_2 \, dw_1,
\]

(A.13)

respectively. Based on [8], \( F_Q(w) \), \( f_{W_1}(w_1) \) and \( f_{W_2}(w_2) \) can be formulated as:

\[
F_Q(w) = 1 - \exp \left( -\frac{w}{\sigma_{md}^2} \right) \sum_{l=0}^{N_R-1} \frac{1}{l!} \left( \frac{w}{\sigma_{md}^2} \right)^l
\]

(A.14)

and

\[
f_{W_1}(w_1) = \frac{w_1^{N_E-1}}{(N_E-1)!} \left( \frac{1}{\sigma_{me}^2} \right)^{N_E} \exp \left( -\frac{w_1}{\sigma_{me}^2} \right)
\]

(A.15)

and

\[
f_{W_2}(w_2) = \frac{w_2^{N_E-1}}{(N_E-1)!} \left( \frac{1}{\sigma_{ke}^2} \right)^{N_E} \exp \left( -\frac{w_2}{\sigma_{ke}^2} \right),
\]

(A.16)

respectively. Substituting (A.14) and (A.15) into (A.12) yields

\[
P_{so,k}^{TAS} = \int_0^\infty \prod_{m \in D, 1 \leq i \leq N_T} F_Q \left( \Lambda_0 + \frac{2^{2R_s}}{H} w \right) f_W(w) \, dw
\]

\[
= \sum_{S'} \sum_{p=0}^{S'} \Psi_0 w^{p+N_E-1} \exp \left( -\frac{w}{\sigma_{me}^2} - \beta_3 2^{2R_s} w \right) \, dw
\]

\[
= \sum_{S'} \sum_{p=0}^{S'} \Psi_0 (p+N_E-1)! \left( \frac{1}{\sigma_{me}^2} + \beta_3 2^{2R_s} \right)^{-p-N_E},
\]

(A.17)

where \( \beta_1 = \frac{(|D| \cdot N_T)'}{N_{R+1} \prod_{l=1}^{N_R} \left( \frac{1}{\sigma_{md}^2} \right)^{n_j} (j-1)!} \), \( \beta_2 = \sum_{j=1}^{N_R} n_j (j-1) \), \( \beta_3 = \frac{1}{\sigma_{me}^2} (|D| \cdot N_T - n_{N_R+1}) \), \( S' = \{(n_1, n_2, \cdots, n_{N_R+1}) | \sum_{i=1}^{N_R+1} n_i = |D| \cdot N_T \} \), and \( \Psi_0 = \frac{\beta_1}{(N_E-1)!} \left( \frac{\beta_2}{\sigma_{me}^2} \right)^{N_E} \left( \frac{2^{2R_s}}{H} \right)^{\beta_2} \left( \frac{\Lambda_0}{2^{2R_s}} \right)^{\beta_3} \).
Using (A.14)-(A.16), we arrive at

\[
F_{\text{TAS}}^{\text{so,k}} = \sum_{S} \sum_{p=0}^{\beta_2} \sum_{t=0}^{p+N_E-1} a_{\beta p} c_{\beta d} \left( \frac{d'_{km}}{p!} + \frac{\beta_3}{\Lambda_1} \right)^{-t-N_E} + \sum_{S} \sum_{p=0}^{\beta_2} \sum_{t=0}^{p+N_E-1} a_{\beta p} d_{\beta d} \left( \frac{c'_km \Lambda_1 + \beta_3 2^{2R_B}}{p!} \right)^{-t-N_E},
\]

where \( a_{\beta p} = \frac{1}{p!} \frac{\beta_2 \Lambda_1}{\sigma_{ke}^2} E_{\text{TAS}}^{(N_E)}(\sum_{l} x_{i,l}^2) \), \( c_{\beta d} = \frac{1}{p!} \frac{\beta_2 \Lambda_1}{\sigma_{ke}^2} E_{\text{TAS}}^{(N_E)}(\sum_{l} x_{i,l}^2) \), and \( d_{\beta d} = \frac{1}{p!} \frac{\beta_2 \Lambda_1}{\sigma_{ke}^2} E_{\text{TAS}}^{(N_E)}(\sum_{l} x_{i,l}^2) \).

**Appendix B**

Upon defining \( X_1 = \max_{i,l} |h_{sm,el}|^2 \), \( X_2 = \max_{i,l} |h_{sk,el}|^2 \), and \( Y = \max_{i,l} |h_{sm,d_m}|^2 \), the expressions \( \Pr(N_T N_R \max_{i,j} |h_{sm,d_m}|^2 < 2^{2R_B} \max_{i,l} |h_{sm,el}|^2) \) and \( \Pr(\max_{i,j} |h_{sm,d_m}|^2 < 2^{2R_B} \frac{1}{N_T N_R} \max_{i,l} |h_{sm,el}|^2) \) can be rewritten as

\[
\Pr \left( \max_{i,j} |h_{sm,d_m}|^2 < 2^{2R_B} \frac{1}{N_T N_R} \max_{i,l} |h_{sm,el}|^2 \right) = \int_{0}^{X_1} \prod_{i,j} F_Y \left( \frac{2^{2R_B} x_1}{N_T N_R} \right) f_{X_1} (x_1) \, dx_1 \tag{B.1}
\]

and

\[
\Pr \left( \max_{i,j} |h_{sm,d_m}|^2 < 2^{2R_B} \frac{1}{N_T N_R} \max_{i,l} |h_{sm,el}|^2 \right) = \int_{0}^{X_1} \prod_{i,j} F_Y \left( \frac{2^{2R_B} x_1}{N_T N_R} \right) f_{X_1} (x_1) f_{X_2} (x_2) \, dx_1 \, dx_2 + \int_{0}^{X_1} \prod_{i,j} F_Y \left( \frac{2^{2R_B} x_2}{N_T N_R \Delta_1} \right) f_{X_2} (x_2) f_{X_1} (x_1) \, dx_2 \, dx_1, \tag{B.2}
\]

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 \( |h_{sm,el}|^2 \) and \( |h_{sk,el}|^2 \) 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:

$$\Pr(X < x) = \Pr\left(\max_{i,l} |h_{s_m,e_l}|^2 < x\right) = \prod_{i,l} \Pr\left(|h_{s_m,e_l}|^2 < x\right)$$

$$= 1 + \sum_{n=1}^{2^{N_T N_E} - 1} (-1)^{|C_n|} \exp\left(-\sum_{i,l \in C_n} \frac{x}{\sigma^2_{s_m,e_l}}\right), \quad (B.3)$$

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 a SN to the eavesdropper $E$ in the second stage.

Hence, the PDF of the RV $X_1$ can be formulated as

$$f_{X_1}(x_1) = \sum_{n=1}^{2^{N_T N_E} - 1} \sum_{i,l \in C_n} \frac{(-1)^{|C_n|+1}}{\sigma^2_{s_m,e_l}} \exp\left(-\sum_{i,l \in C_n} \frac{x_1}{\sigma^2_{s_m,e_l}}\right). \quad (B.4)$$

Similarly, the PDF of the RV $X_2$ is given by

$$f_{X_2}(x_2) = \sum_{n=1}^{2^{N_E} - 1} \sum_{l \in F_g} \frac{(-1)^{|F_g|+1}}{\sigma^2_{s_k,e_l}} \exp\left(-\sum_{l \in F_g} \frac{x_2}{\sigma^2_{s_k,e_l}}\right), \quad (B.5)$$

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 a SN to the eavesdropper $E$ in the first stage.

Furthermore, $\prod_{i,j} F_Y\left(\frac{2^{2R_B}}{N_T N_R} \frac{x_1}{x_1} \right)$ can be expanded as

$$\prod_{i,j} F_Y\left(\frac{2^{2R_B}}{N_T N_R} \frac{x_1}{x_1} \right) = \prod_{i,j} \left(1 - \exp\left(-\frac{2^{2R_B}}{N_T N_R} \frac{x_1}{\sigma^2_{s_m,d_m}}\right)\right). \quad (B.6)$$

For notational convenience, we introduce $Z_1 = -\frac{2^{2R_B}}{N_T N_R} \frac{x_1}{\sigma^2_{s_m,d_m}}$, and $Z_2 = -\frac{2^{2R_B}}{N_T N_R} \frac{x_2}{\sigma^2_{s_m,d_m}}$. 

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Then, $E(Z_1)$ is given by

$$
E(Z_1) = \int_0^\infty \left( \frac{2^{2R_b}}{N_T N_R \sigma_{s_m,d_m}^2} x_1 \right) f_{X_1}(x_1) f_{X_2}(x_2) \, dx_1 dx_2
$$

$$
= \sum_{n=1}^{2^{N_T N_R - 1}} \sum_{t=0}^{1} \frac{1}{\Delta_t} \frac{t^{2^{R_b} \alpha_{n} \sigma_{e} \lambda_{se}}}{N_T N_R (1 - t)!} \lambda_{se},
$$

(B.7)

where $\alpha_{n} = \frac{2^{R_b} \alpha_{s_m,d_m}}{N_T N_R \sigma_{s_m,d_m}^2}$. 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 [23],

$$
1 - \exp\left(-\frac{1}{N_T N_R \sigma_{s_m,d_m}^2} \frac{2^{2R_b} x}{\Delta_1 N_T N_R} \right)
\leq \frac{2^{2R_b} x}{N_T N_R \sigma_{s_m,d_m}^2}
$$

(B.8)

Hence, $\prod_{i,j} F_Y(\frac{2^{2R_b} x}{N_T N_R \sigma_{s_m,d_m}^2})$ and $\prod_{i,j} F_Y(\frac{2^{2R_b} x}{\Delta_1 N_T N_R})$ can be rewritten as

$$
\prod_{i,j} F_Y(\frac{2^{2R_b} x}{N_T N_R \sigma_{s_m,d_m}^2}) = \left( \frac{2^{2R_b} x}{N_T N_R} \right)^{N_T N_R} \prod_{i,j} \frac{1}{\sigma_{s_m,d_m}^2} x^{N_T N_R}
$$

(B.9)

and

$$
\prod_{i,j} F_Y(\frac{2^{2R_b} x}{\Delta_1 N_T N_R}) = \left( \frac{2^{2R_b} x}{\Delta_1 N_T N_R} \right)^{N_T N_R} \prod_{i,j} \frac{1}{\sigma_{s_m,d_m}^2} x^{N_T N_R},
$$

(B.10)

respectively.

Substituting (B.4) and (B.9) into (B.1) yields

$$
\Pr \left( N_T N_R \max_{i,j} \left| h_{s_m,d_m} \right|^2 > \frac{2^{2R_b} \max_{i,l} \left| h_{s_m,e_l} \right|^2} {\sigma_{s_m,d_m}^2} \right)
$$

$$
= \sum_{n=1}^{2^{N_T N_R - 1}} \left( \frac{2^{2R_b}}{N_T N_R} \right)^{N_T N_R} \prod_{i,j} \frac{1}{\sigma_{s_m,d_m}^2} \cdot \sum_{i \in C_n} \frac{(-1)^{|C_n|+1}}{\sigma_{s_i,e_i}^2} \int_0^\infty x^{N_T N_R} \exp\left(-\sum_{i \in C_n} \frac{x}{\sigma_{s_i,e_i}^2} \right) \, dx
$$

$$
= \sum_{n=1}^{2^{N_T N_R - 1}} \left( \frac{2^{2R_b}}{N_T N_R} \right)^{N_T N_R} (N_T N_R)!(-1)^{|C_n|+1} \cdot \sum_{i \in C_n} \frac{1}{\sigma_{s_i,e_i}^2} \prod_{i,j} \frac{1}{\sigma_{s_m,d_m}^2}.
$$

(B.11)

For notational convenience, upon denoting $\sigma_{s_m,e_l}^2 = \alpha_{s_m,e_l} \sigma_{s_m,e_l}^2$, $\sigma_{s_k,e_l}^2 = \alpha_{s_k,e_l} \sigma_{s_k,e_l}^2$, $\sigma_{s_m,d_m}^2 = \sigma_{s_m,d_m}^2$ and $\sigma_{s_k,d_m}^2 = \sigma_{s_k,d_m}^2$,
\[ \alpha_{s_m d_m} \sigma^2_{m d}, \] we have

\[ \Pr \left( N_T N_R \max_{i,j} \left| h_{s_m d_m} \right|^2 < 2^{\frac{2R_B}{N_T N_R}} \max_{i,l} \left| h_{s_m e_l} \right|^2 \right) = \sum_{n=1}^{2^{N_T N_R - 1}} (-1)^{C_n + 1} \omega_{i0} \left( \frac{1}{\lambda_{se}} \right)^{N_T N_R}, \tag{B.12} \]

where \( \omega_{i0} = (N_T N_R)! \left( \frac{2R_B}{N_T N_R} \right) \sum_{i,j \in C_m} \alpha_{s_m d_m}^{-1}. \)

Similarly to (B.12), (B.2) can be obtained as

\[ \Pr \left( N_T N_R \max_{i,j} \left| h_{s_m d_m} \right|^2 < 2^{\frac{2R_B}{N_T N_R}} \max_{i,l} \left( \max_{i,l} \left| h_{s_m e_l} \right|^2, \frac{1}{\Delta_1} \max_{l} \left| h_{s_k e_l} \right|^2 \right) \right) \]

\[ = \sum_{n=1}^{2^{N_T N_R - 1}} \sum_{g=1}^{2^{N_T N_R - 1}} \sum_{t=0}^{N_T N_R} (-1)^{C_n + 1} \alpha_{i0} \left( \frac{1}{\lambda_{se}} \right)^{N_T N_R} + \sum_{n=1}^{2^{N_T N_R - 1}} \sum_{g=1}^{2^{N_T N_R - 1}} \sum_{t=0}^{N_T N_R} (-1)^{C_n + 1} \beta_{i0} \left( \frac{1}{\lambda_{se}} \right)^{N_T N_R}, \tag{B.13} \]

where \( \alpha_{i0} = \sum_{i,l \in C_n} \Delta_i \alpha_{s_m e_l} + \sum_{l \in F_g} \frac{1}{\alpha_{s_k e_l}}, \alpha_{i0} = \left( \sum_{i,l \in C_n} \frac{1}{\alpha_{s_m e_l}} \right) \prod_{l \in F_g} \frac{1}{\alpha_{s_k e_l}} \right)^{N_T N_R} \]

\[ \frac{2R_B}{N_T N_R} \left( \sum_{i,l \in C_n} \frac{1}{\alpha_{s_m e_l}} \right) \prod_{l \in F_g} \frac{1}{\alpha_{s_k e_l}}. \]

Similarly to (B.11) and (B.13), \( \Pr(\max_{m,i,j} \left| h_{s_m d_m} \right|^2 < 2^{\frac{2R_B}{N_T N_R}} \max_{i,l} \left| h_{s_m e_l} \right|^2) \) and

\[ \Pr(\max_{m,i,j} \left| h_{s_m d_m} \right|^2 < 2^{\frac{2R_B}{N_T N_R}} \max_{i,l} \left( \max_{i,l} \left| h_{s_m e_l} \right|^2, \frac{1}{\Delta_1} \max_{l} \left| h_{s_k e_l} \right|^2 \right)) \]

\[ \text{can be rewritten as} \]

\[ \Pr \left( \max_{m,i,j} \left| h_{s_m d_m} \right|^2 < \frac{1}{N_T N_R} \left( \frac{2R_B}{N_T N_R} \max_{i,l} \left| h_{s_m e_l} \right|^2 \right) \right) = \sum_{n=1}^{2^{N_T N_R - 1}} (-1)^{C_n + 1} \omega_{m0} \left( \frac{1}{\lambda_{se}} \right)^{N_T N_R}, \tag{B.14} \]

and

\[ \Pr \left( \max_{m,i,j} \left| h_{s_m d_m} \right|^2 < \frac{1}{N_T N_R} \left( \frac{2R_B}{N_T N_R} \max_{i,l} \left( \max_{i,l} \left| h_{s_m e_l} \right|^2, \frac{1}{\Delta_1} \max_{l} \left| h_{s_k e_l} \right|^2 \right) \right) \right) \]

\[ = \sum_{n=1}^{2^{N_T N_R - 1}} \sum_{g=1}^{2^{N_T N_R - 1}} \sum_{t=0}^{N_T N_R} (-1)^{C_n + 1} \alpha_{m0} \left( \frac{1}{\lambda_{se}} \right)^{N_T N_R} + \sum_{n=1}^{2^{N_T N_R - 1}} \sum_{g=1}^{2^{N_T N_R - 1}} \sum_{t=0}^{N_T N_R} (-1)^{C_n + 1} \beta_{m0} \left( \frac{1}{\lambda_{se}} \right)^{N_T N_R}, \tag{B.15} \]

respectively, where \( \alpha_{m0} = \frac{(MN_T N_R)! \left( \sum_{i,l \in C_n} \frac{1}{\alpha_{s_m e_l}} \right) \prod_{l \in F_g} \frac{1}{\alpha_{s_k e_l}} \right)^{N_T N_R} \]

\[ \frac{2R_B}{N_T N_R} \left( \sum_{i,l \in C_n} \frac{1}{\alpha_{s_m e_l}} \right) \prod_{l \in F_g} \frac{1}{\alpha_{s_k e_l}}. \]

\( \omega_{m0} = \frac{(MN_T N_R)! \left( \sum_{i,l \in C_n} \frac{1}{\alpha_{s_m e_l}} \right) \prod_{l \in F_g} \frac{1}{\alpha_{s_k e_l}} \right)^{N_T N_R} \]

\( \frac{2R_B}{N_T N_R} \left( \sum_{i,l \in C_n} \frac{1}{\alpha_{s_m e_l}} \right) \prod_{l \in F_g} \frac{1}{\alpha_{s_k e_l}}. \)
REFERENCES

[1] S. Lin, L. Kong, Q. Gao, et al., “Advanced dynamic channel access strategy in spectrum sharing 5G systems,” Proceedings of the IEEE, vol. 24, no. 5, pp. 74-80, Oct. 2017.

[2] S. K. Sharma, T. E. Bogale, L. B. Le, et al., “Dynamic spectrum sharing in 5G wireless networks with full-duplex technology: Recent advances and research challenges,” IEEE Commun. Surveys Tutorials, vol. 20, no. 1, pp. 674-707, 2018.

[3] J. Mitola, J. Guerci, J. Reed, et al., “Accelerating 5G QoE via public-private spectrum sharing,” IEEE Trans. Wireless Commun., vol. 52, no. 5, pp. 77-85, May. 2014.

[4] N. Zhang, S. Zhang, J. Zheng, X. Fang, J. Mark and X. Shen “QoE driven decentralized spectrum sharing in 5G networks: Potential game approach,” IEEE Trans. Veh. Technol., vol. 66, no. 9, pp. 7797-7808, Mar. 2017.

[5] A. D. Wyner, “The wire-tap channel,” Bell System Technical Journal, vol. 54, no. 8, pp. 1355-1387, 1975.

[6] S. K. Leung-Yan-Cheong and M. E. Hellman, “The Gaussian wiretap channel,” IEEE Trans. Inf. Theory, vol. 24, no. 4, pp. 451-456, Jul. 1978.

[7] Y. Zou, X. Li and Ying-Chang Liang, “Secrecy outage and diversity analysis of cognitive radio systems,” IEEE J. Sel. Areas in Commun., vol. 32, no. 11, pp. 2222-2236, Nov. 2014

[8] H. Lei, H. Zhang, I. Ansari, C. Gao, Y. Guo, G. Pan and K. Qaraqe, “Secrecy outage performance for SIMO underlay cognitive radio systems with generalized selection combining over Nakagami-m channels,” IEEE Trans. Veh. Technol., vol. 65, no. 12, pp. 10126-10132, Dec. 2016.

[9] H. Lei, M. Xu, I. Ansari, G. Pan, K. Qaraqe and M. Alouini, “On secure underlay MIMO cognitive radio networks with energy harvesting and transmit antenna selection,” IEEE Trans. Green Commun. and Netw., vol. 1, no. 2, pp. 192-203, Jun. 2017.

[10] B. Wang, P. Mu and Z. Li, “Artificial-noise-aided beamforming design in the MISOME wiretap channel under the secrecy outage probability constraint,” IEEE Trans. Wireless Commun., vol. 16, no. 11, pp. 7207-7220, Nov. 2017.

[11] C. Jeong, I. Kim and K. Dong, “Joint secure beamforming design at the source and the relay for an amplify-and-forward MIMO untrusted relay system,” IEEE Trans. Signal Process., vol. 60, no. 1, pp. 310-325, Jan. 2012.

[12] J. Xu, L. Duan and R. Zhang, “Proactive eavesdropping via cognitive jamming in fading channels,” IEEE Trans. Wireless Commun., vol. 16, no. 5, pp. 2790-2806, May 2017.

[13] N. Nguyen, H. Ngo, T. Duong, H. Tuan and K. Tourki, “Secure massive MIMO with the artificial noise-aided downlink training,” IEEE J. Sel. Areas in Commun., vol. 36, no. 4, pp. 802-816, Apr. 2018.

[14] A. Abd El-Malek, A. Salhab, S. Zummo and M. S. Alouini, “Security-reliability trade-off analysis for multiuser SIMO mixed RF/FSO relay networks with opportunistic user scheduling,” IEEE Trans. Wireless Commun., vol. 15, no. 9, pp. 5904-5918, Sep. 2016.

[15] I. Bang, S. Kim and D. Sung, “Artificial noise-aided user scheduling for optimal secrecy multiuser diversity,” IEEE Commun. Lett., vol. 21, no. 3, pp. 528-531, Mar. 2017.
[16] T. Zheng, H. Wang, F. Liu, and M. Lee, “Outage constrained secrecy throughput maximization for DF relay networks,” IEEE Trans. Commun., vol. 63, no. 5, pp. 1741-1755, May 2015.

[17] H. Wang, K. Huang, Q. Yang and Z. Han, “Joint source-relay secure precoding for MIMO relay networks with direct links,” IEEE Trans. Commun., vol. 65, no. 7, pp. 2781-2793, Jul. 2017.

[18] X. Ding, T. Song, Y. Zou, X. Chen and L. Hanzo, “Security-reliability tradeoff analysis of artificial noise aided two-way opportunistic relay selection,” IEEE Trans. Veh. Tech., vol. 66, no. 5, pp. 3930-3941, May 2017.

[19] A. El-Malek, A. Salhab and S. Zummo, “New bandwidth efficient relaying schemes in cooperative cognitive two-way relay networks with physical layer security,” IEEE Trans. Veh. Tech., vol. 66, no. 6, pp. 5372-5386, Jun. 2017.

[20] T. Lv, H. Gao and S. Yang, “Secrecy transmit beamforming for heterogeneous networks,” IEEE J. Sel. Areas in Commun., vol. 33, no. 6, pp. 1154-1170, Jun. 2015.

[21] W. Tang, S. Feng, Y. Ding and Y. Liu, “Physical layer security in heterogeneous networks with jammer selection and full-duplex users,” IEEE Trans. Wireless Commun., vol. pp, no. 99, pp. 7982-7995, 2017.

[22] H. Wang, T. Zheng, J. Yuan, D. Towsley and M. Lee, “Physical layer security in heterogeneous cellular networks,” IEEE Trans. Commun., vol. 64, no. 3, pp. 1204-1219, Mar. 2016.

[23] J. Zhu, Y. Zou, G. Wang, Y. D. Yao and G. K. Karagiannidis, “On secrecy performance of antenna-selection-aided MIMO systems against eavesdropping,” IEEE Trans. Veh. Tech., vol. 65, no. 1, pp. 214-225, Jan. 2016.

[24] Y. Zou, “Physical-layer security for spectrum sharing systems,” IEEE Trans. Wireless Commun., vol. 16, no. 2, pp. 1319-1329, Feb. 2017.

[25] Y. Tolossa, S. Vuppala and G. Abreu, “Secrecy-rate analysis in multitier heterogeneous networks under generalized fading model,” IEEE Internet of Things J., vol. 4, no. 1, pp. 101-110, Feb. 2017.

[26] J. Zhao, T. Q. S. Quek and Z. Lei, “Heterogeneous cellular networks using wireless backhaul: Fast admission control and large system analysis,” IEEE J. Sel. Areas in Commun., vol. 33, no. 10, pp. 2128-2143, Oct. 2015.

[27] N. Yang, P. L. Yeoh, M. Elkashlan, R. Schober, and I. B. Collings, “Transmit antenna selection for security enhancement in MIMO wiretap channels,” IEEE Trans. Commun., vol. 61, no. 1, pp. 144-154, Jan. 2013.

[28] L. Zheng and D. Tse, “Diversity and multiplexing: A fundamental tradeoff in multiple antenna channels,” IEEE Trans. Inf. Theory, vol. 49, no. 5, pp. 1073-1096, May 2003.

[29] Y. Zou, Y. D. Yao, and B. Zheng, “An adaptive cooperation diversity scheme with best-relay selection in cognitive radio networks,” IEEE Trans. Signal Process., vol. 58, no. 10, pp. 5438-5445, Oct. 2010.