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Physical-layer security enhancement method for wireless HetNets via transmission pair scheduling

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Abstract: In order to enhance the physical-layer security of wireless transmission in a wireless heterogeneous network (HetNet), a two-stage-based cooperative framework is advocated. To be specific, a source-destination (SD) pair is opportunistically chosen at the beginning of the transmission slot, which can be used to assist the transmissions of other SD pairs. Under this framework, a transmit antenna selection assisted opportunistic SD pair scheduling (TAS-OSDS) scheme is proposed, and the intercept probability (IP) of the proposed TAS-OSDS, the conventional round-robin source-destination pair scheduling (RSDS) and the conventional non-cooperation (non-coop) schemes is also analyzed, where the RSDS and non-coop schemes are used for comparison with the proposed TAS-OSDS. Numerical results show that increasing the number of the SD pairs can effectively reduce the IP of the TAS-OSDS scheme, whereas the IP of the RSDS and the non-coop remain unchanged with an increasing number of the SD pairs. Furthermore, the TAS-OSDS scheme achieves a lower IP than that of the RSDS and the non-coop schemes, showing the superiority of the proposed TAS-OSDS.

Key words: wireless heterogeneous network; physical-layer security; source-destination pair scheduling

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Wireless heterogeneous networks are capable of increasing the efficiency and flexibility of wireless systems, which are composed of various independent subsystems[1-2]. In a heterogeneous wireless network, various subsystems may be allowed to perform their respective wireless transmissions simultaneously. However, due to the broadcast nature of radio propagation[3], and the open system architecture of heterogeneous wireless networks[4], the confidential messages may be vulnerable to eavesdropping attacks when they are transmitted by heterogeneous wireless systems independently. Thus, the risk of confidential messages being successfully eavesdropped upon will be increased significantly. As a result, more research efforts should be devoted to protecting wireless transmissions transmitted by heterogeneous wireless networks against malicious eavesdropping.

Physical-layer security (PLS)[5-6] emerges as an effective method to guard against wiretapping with the aid of its ability to exploit the physical characteristics of wireless channels. Recently, PLS has also been designed for spectrum-sharing aided heterogeneous networks[7-8]. Jamming schemes were investigated in Ref. [9]. To be specific, in order to impose an interference on the eavesdroppers, the jammers were invoked to transmit jamming signals, whereas the amount of the interference imposed on the scheduled users was considered to be below a threshold. Single-input multiple-output (SIMO) and multiple-input multiple-output (MIMO) techniques[10-11] have been investigated to decrease the secrecy outage probability of wireless transmissions. In Ref. [12], the antenna selection was conceived to improve the PLS of wireless transmissions in the presence of an eavesdropper.

In this paper, we investigate the PLS of a heterogeneous wireless network consisting of multiple SD pairs in the presence of an eavesdropper. Differing from Refs. [7 - 12], the cooperation between various SD pairs has been explored to defend against malicious eavesdropping relying on a conceived cooperative framework. Moreover, we propose an SD pair scheduling scheme to improve the PLS of wireless transmissions. The main contributions of this paper can be summarized as follows. First, a heterogeneous cooperative framework is conceived to protect wireless transmissions against eavesdropping with the aid of two stages. Secondly, we propose a specific SD pair scheduling scheme, called the TAS-OSDS. In the TAS-OSDS scheme, one antenna of the chosen SD will be selected to transmit the repacked data to enhance the PLS of the transmitted data. Finally, it is shown that the IP of TAS-OSDS scheme will be benefi-

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cially reduced by increasing the number of SD transmission pairs.

1 System Model and Opportunistic SD Scheduling

1.1 System model

As shown in Fig. 1, we investigate a wireless system consisting of M source-destination (SD) pairs in the presence of an eavesdropper E, where an source node (SN) S_m has the ability to communicate both with its corresponding destination node (DN) D_m, $m \in \{1, 2, \ldots, M\}$, and with other SNs at different transmission stages. For notational convenience, the set of SD pairs is assumed to be denoted as Φ. E with the aid of a wide-band receiver is deployed to wiretap the signal transmitted by the legitimate SD pairs. Moreover, we also assume that all DNs are connected with each other through the core network, and thus, each DN has the ability to forward the received data to other DNs. Furthermore, Rayleigh fading is used to characterize both the main links (spanning from the legitimate transmitters to the legitimate receivers) and the wiretap links (spanning from the legitimate transmitters to the eavesdropper).

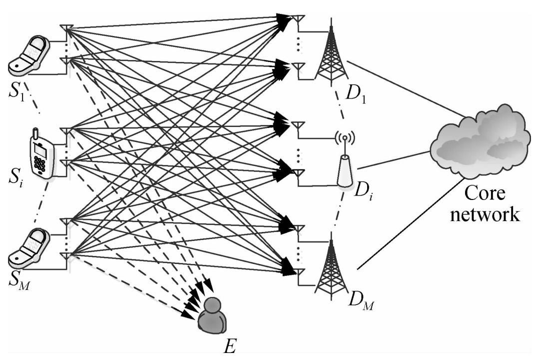

Fig. 1 A heterogeneous wireless network with M multiple source-destination pairs in the presence of an eavesdropper

In order to improve the PLS of wireless transmissions of the multiple SD pairs, a heterogeneous cooperative framework is invoked with the aid of two stages. More specifically, at the beginning of the first stage, an SD pair will be chosen to be a transmitting node relying on the criterions of the RSDS and the TAS-OSDS schemes. Then, in order to help other SNs to forward their data, the chosen SD pair will receive the data of other SNs through a high-reliability low-power interface, and then repack the received data and its own data. At the second stage, the specifically selected SN may forward the repacked packet to its DN. After decoding the packet, the DN will send the sub-packets to the other DNs relying on the index of the pair in the sub-packet via the core network.

1.2 Signal model

Without loss of generality, S_m is assumed to be the selected transmitting node in the first stage. As mentioned above, other SNs will transmit their signal to S_m. Moreover, we also assume that only one antenna of S_k is chosen to transmit its data to S_m, which is represented by antenna i. Hence, the signal received at S_m transmitted by S_k, $k \in \Phi - \{m\}$, can be shown as

$$y_{s_k s_m} = \sum_{j=1}^{N_T} \sqrt{P_s} h_{s_{k_i} s_{m_j}} x_k + n_{s_m} \tag{1}$$

where P_s, x_k, $h_{s_{k_i} s_{m_j}}$ and n_{s_m} are the transmit power of S_k, the transmit signal of S_k, the instantaneous channel gain of the S_{k_i}-S_{m_j} link, and the thermal noise received at S_m, respectively. Moreover, N_T is the number of antennas of S_m. Meanwhile, since the broadcast nature of radio propagation, E may also overhear the signal transmitted by S_k, which can be given 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 encountered at E, and $h_{s_k e_l}$ denotes the channel gain of S_{k_i}-E_l link.

From Eq. (2), and using maximal-ratio combining (MRC), we can obtain the channel capacity of the S_k-E link as

$$C_{se}^k = \log_2(1 + \gamma_{s_k e}) \tag{3}$$

where $\gamma_{s_k e} = \sum_{l=1}^{N_E} \frac{P_s |h_{s_k e_l}|^2}{N_0}$ denotes the received signal-to-noise (SNR) at E of the S_k-E link; N_0 denotes the variance of thermal noise of D_m and E; and N_E denote the number of antennas of E.

In the second stage, we also assume that one antenna of S_m is invoked for forwarding the received data to D_m. Without loss of generality, we assume that the antenna i of S_m, $i \in \{1, 2, \ldots, N_T\}$, is chosen to transmit packet x_s to D_m. Hence, the signal received at D_m can be expressed as

$$y_{s_m d_m} = \sum_{j=1}^{N_R} \sqrt{P_t} h_{s_{m_i} d_{m_j}} x_s + n_{d_m} \tag{4}$$

where $h_{s_{m_i} d_{m_j}}$ and n_{d_m} denote the channel gain of the S_{m_i}-D_{m_j} link, and the thermal noise encountered at S_m, respectively. Moreover, N_R denotes the number of antennas of D_m, and P_t represents the transmit power of S_m.

Similarly to Eq. (2), E may overhear the signal transmitted by S_m, which is

$$y_{s_m e} = \sum_{l=1}^{N_E} \sqrt{P_t} h_{s_{m_i} e_l} x_s + n_e \tag{5}$$

where $h_{s_{m_i} e_l}$ denotes the channel gain of the S_{m_i}-E_l link.

With the aid of Eq. (4) and MRC, the instantaneous channel capacity of the S_m-D_m link can be obtained as

$$C_{s_m d_m} = \log_2(1 + \gamma_{s_m d_m}) \tag{6}$$

where $\gamma_{s_m d_m} = \sum_{j=1}^{N_R} \frac{P_t |h_{s_{m_i} d_{m_j}}|^2}{N_0}$.

Utilizing Eq. (5) and MRC, we can obtain the instantaneous channel capacity of the S_m-E link as

$$C_{se}^{m} = \log_2(1 + \gamma_{s_m e}) \tag{7}$$

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

From Eq. (3) and Eq. (7), and utilizing the maximum of individual channel capacity of the S_m-E and S_k-E links in the first and second stages, we can obtain the overall capacity of the signal from S_k as

$$C_{s_m e}^{k} = \max(C_{se}^{k}, C_{se}^{m}) = \log_2(1 + \max(\gamma_{s_m e}, \gamma_{s_k e})) \tag{8}$$

In contrast, since the signal from S_m is only transmitted at the second stage, the overall capacity of the signal of S_m can still be given as

$$C_{s_m e}^{m} = C_{se}^{m} = \log_2(1 + \gamma_{s_m e}) \tag{9}$$

Noting that given the chosen transmission pair, the signal of the chosen SD will only be overheard by E once, due to the fact that it is only transmitted at the second stage. Differing from the chosen SD, the signal of other SDs will be overheard both in the first state and in the second stage, which are represented by Eq. (2) and Eq. (5), respectively.

1.3 TAS assisted opportunistic SD scheduling scheme

In this subsection, a TAS assisted opportunistic SD scheduling (TAS-OSDS) scheme is proposed. Specifically, in order to enhance the PLS of wireless transmissions of multiple SD pairs, an SN with the maximal channel capacity in set Φ will be chosen to be as the transmitting node at the given time slot, which will help other SNs to forward their data to their DNs. Hence, relying on Eq. (6), the SD pair scheduling criterion of the TAS-OSDS scheme can be shown as

$$\{o, a\} = \arg \max_{m \in \Phi, 1 \leqslant i \leqslant N_T} C_{s_m d_m} \tag{10}$$

where o represents the index of the chosen SD pair in the TAS-OSDS scheme, and a denotes the index of the selected antenna of the chosen S_o. Moreover, Eq. (10) can be rewritten as

$$\{o, a\} = \arg \max_{m \in \Phi, 1 \leqslant i \leqslant N_T} \sum_{j=1}^{N_R} |h_{s_{m_i} d_{m_j}}|^2 \tag{11}$$

which can be performed in a distributed manner. The processing procedure of the TAS-OSDS scheme is shown as follows:

1) Assume that the number of SD pairs is M, and each SN is required to maintain N_T timers.

2) At the beginning of the first stage, the TAS-OSDS scheme will be triggered.

3) Each SD estimates the instantaneous channel state information, and the initial value of each timer is set inversely proportionally to $\sum_{j=1}^{N_R} |h_{s_{m_i} d_{m_j}}|^2$. Thus, o and a can be determined, according to which the timer becomes zero first.

4) S_o will notify other SNs that it is the optimal node via broadcasting a notification. Then, other SNs transmit their data to S_o, which will repack the received data and their own data.

5) At the second stage, S_o will forward the repacked data to its corresponding DN relying on a-th antenna of S_o. Once the transmission is finished, D_o will send other SNs' data to their corresponding DNs relying on the core network.

2 Intercept Probability Analysis over Rayleigh Fading Channels

In this section, we analyze the intercept probability of the RSDS and TAS-OSDS schemes over Rayleigh fading channels.

2.1 Conventional RSDS scheme

As a benchmarking scheme, we present the IP analysis of the traditional RSDS scheme. With the conventional RSDS scheme, each SD pair in set Φ has the same chance to be chosen to transmit at the given time slot. Based on the definition of the IP[12], the IP of the signal from S_m and S_k in the first and second stages for the RSDS scheme relying on the S_m-D_m pair can be shown as

$$P_{\mathrm{int}\_m\_m}^{\mathrm{RSDS}} = \Pr(C_{s_m d_m} < C_{s_m e}^{m}) \tag{12}$$

and

$$P_{\mathrm{int}\_k\_m}^{\mathrm{RSDS}} = \Pr(C_{s_m d_m} < C_{s_m e}^{k}) \tag{13}$$

Combining Eqs. (6), (8) and (9), we can obtain

$$P_{\mathrm{int}\_m\_m}^{\mathrm{RSDS}} = \Pr\left(\sum_{j=1}^{N_R} |h_{s_m d_{m_j}}|^2 < \sum_{l=1}^{N_E} |h_{s_m e_l}|^2\right) \tag{14}$$

and

$$P_{\mathrm{int}\_k\_m}^{\mathrm{RSDS}} = \Pr\left(\sum_{j=1}^{N_R} |h_{s_m d_{m_j}}|^2 < \max\left(\sum_{l=1}^{N_E} |h_{s_{m_i} e_l}|^2, \frac{1}{\Delta_1}\sum_{l=1}^{N_E} |h_{s_k e_l}|^2\right)\right) \tag{15}$$

where $\Delta_1 = P_t/P_s$. Additionally, from Eqs. (14) and (15), we can see that SD pairs are selected without taking the random variables (RVs) $|h_{s_m d_{m_j}}|^2$ and $|h_{s_m e_l}|^2$ into account in the RSDS scheme. For simplicity, we make the following assumption, which is a common assumption and it is widely adopted. Specifically, given transmission SD pair m, we assume that the fading coefficients of all the links between SNs and DNs, denoted as $|h_{s_{m_i} d_{m_j}}|^2$ for $i \in \{1, 2, \ldots, N_T\}$, $j \in \{1, 2, \ldots, N_R\}$, are independent and identically distributed (i. i. d.) RVs having the same mean $\sigma_{md}^2 = E(|h_{s_m d_{m_j}}|^2)$. Similarly, the fading coefficients of the wiretap links $|h_{s_{m_i} e_l}|^2$ for $i \in \{1, 2, \ldots, N_T\}$, $l \in \{1, 2, \ldots, N_E\}$, are also assumed to be i. i. d RVs with the same average channel gain $\sigma_{me}^2 = E(|h_{s_m e_l}|^2)$. Then, denoting $U = \sum_{j=1}^{N_R} |h_{s_m d_{m_j}}|^2$, $X_1 = \sum_{l=1}^{N_E} |h_{s_m e_l}|^2$, and $X_2 = \sum_{l=1}^{N_E} |h_{s_k e_l}|^2$, due to RVs $|h_{s_m d_{m_j}}|^2$, $|h_{s_k e_l}|^2$, and $|h_{s_m e_l}|^2$ are independent of each other, $P_{\text{int\_}m\text{\_}m}^{\text{RSDS}}$ and $P_{\text{int\_}k\text{\_}m}^{\text{RSDS}}$ can be shown as

$$P_{\text{int\_}m\text{\_}m}^{\text{RSDS}} = \Pr\left(\sum_{j=1}^{N_R} |h_{s_m d_{m_j}}|^2 < \sum_{l=1}^{N_E} |h_{s_m e_l}|^2 \right) = \int_0^\infty F_U(x_1) f_{X_1}(x_1)\,\mathrm{d}x_1 \tag{16}$$

$$P_{\text{int\_}k\text{\_}m}^{\text{RSDS}} = \Pr\left(\sum_{j=1}^{N_R} |h_{s_m d_{m_j}}|^2 < \max\left(\sum_{l=1}^{N_E} |h_{s_m e_l}|^2, \frac{1}{\Delta_1} \sum_{l=1}^{N_E} |h_{s_k e_l}|^2 \right) \right) = \int_0^\infty \int_{x_2/\Delta_1}^\infty F_U(x_1) f_{X_1}(x_1) f_{X_2}(x_2)\,\mathrm{d}x_1 \mathrm{d}x_2 = \int_0^\infty \int_{\Delta_1 x_1}^\infty F_U\left(\frac{1}{\Delta_1} x_2\right) f_{X_2}(x_2) f_{X_1}(x_1)\,\mathrm{d}x_2 \mathrm{d}x_1 \tag{17}$$

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 function (PDF) of RVs X_1 and X_2, respectively. Based on Ref. [8], they can be given by

$$F_U(x_1) = 1 - \exp\left(-\frac{x_1}{\sigma_{md}^2}\right) \sum_{l=0}^{N_R-1} \frac{1}{l!} \left(\frac{x_1}{\sigma_{md}^2}\right)^l \tag{18}$$

$$f_{X_1}(x_1) = \frac{x_1^{N_E-1}}{(N_E-1)!} \left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \exp\left(-\frac{x_1}{\sigma_{me}^2}\right) \tag{19}$$

$$f_{X_2}(x_2) = \frac{x_2^{N_E-1}}{(N_E-1)!} \left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \exp\left(-\frac{x_2}{\sigma_{me}^2}\right) \tag{20}$$

Substituting Eqs. (18) and (19) into Eq. (16) yields

$$P_{\text{int\_}m\text{\_}m}^{\text{RSDS}} = \int_0^\infty F_U(x_1) f_{X_1}(x_1)\,\mathrm{d}x_1 = 1 - \sum_{l=0}^{N_R-1} \frac{(l+N_E-1)!}{l!(N_E-1)!} \left(\frac{1}{\sigma_{md}^2}\right)^l \cdot \left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \left(\frac{1}{\sigma_{me}^2} + \frac{1}{\sigma_{md}^2}\right)^{-l-N_E} \tag{21}$$

Substituting Eqs. (18), (19) and (20) into Eq. (17) yields

$$P_{\text{int\_}k\text{\_}m}^{\text{RSDS}} = \sum_{t=0}^{N_E-1} \left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \left(\frac{1}{\sigma_{me}^2 \Delta_1}\right)^t \frac{(t+N_E-1)!}{t!(N_E-1)!} c_{km}^{-t-N_E} - \sum_{l=0}^{N_R-1} \sum_{t=0}^{l+N_E-1} a_{lp} c_{md} \left(c_{km} + \frac{1}{\Delta_1 \sigma_{md}^2}\right)^{-t-N_E} + \sum_{t=0}^{N_E-1} \left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \left(\frac{\Delta_1}{\sigma_{me}^2}\right)^t \frac{(t+N_E-1)!}{t!(N_E-1)!} d_{km}^{-t-N_E} - \sum_{l=0}^{N_R-1} \sum_{t=0}^{l+N_E-1} a'_{lp} d_{kd} \left(d_{km} + \frac{1}{\sigma_{md}^2}\right)^{-t-N_E} \tag{22}$$

where

$$a_{lp} = \frac{\left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \left(\frac{1}{\sigma_{me}^2}\right)^{N_E} \left(\frac{1}{\sigma_{md}^2}\right)^l}{l!\,t!\,(N_E-1)!\,(N_E-1)!}$$

$$c_{md} = \left(\frac{1}{\sigma_{me}^2} + \frac{1}{\sigma_{md}^2}\right)^{-l-N_E+t} \Delta_1^{-t} (l+N_E-1)!\,(t+N_E-1)!$$

$$d_{kd} = \left(\frac{1}{\sigma_{me}^2} + \frac{1}{\Delta_1 \sigma_{md}^2}\right)^{-l-N_E+t} \Delta_1^{t-l} (t+N_E-1)!\,(l+N_E-1)!$$

$$c_{km} = \frac{1}{\sigma_{me}^2} + \frac{1}{\Delta_1 \sigma_{me}^2},\quad d_{km} = \frac{\Delta_1}{\sigma_{me}^2} + \frac{1}{\sigma_{me}^2}$$

We assume that each SD has the same weighting coefficient. Hence, the IP of the investigated system relying on S_m can be defined as

$$P_{\text{int\_}m}^{\text{RSDS}} = \frac{1}{M} \sum_{k \in \Phi - \{i\}} P_{\text{int\_}k\text{\_}m}^{\text{RSDS}} + P_{\text{int\_}m\text{\_}m}^{\text{RSDS}} \tag{23}$$

As previously mentioned, each SD pair can be selected to transmit with equal opportunity in the RSDS scheme. Moreover, relying on the law of total probability[13], the IP of the multiple SD pairs in the RSDS scheme can be given by

$$P_{\text{int}}^{\text{RSDS}} = \frac{1}{M} \sum_{m=1}^{M} P_{\text{int\_}m}^{\text{RSDS}} \tag{24}$$

2.2 Proposed TAS-OSDS scheme

This subsection presents the IP analysis of the TAS-OSDS scheme. As shown in Eq. (10), the index of the chosen SD pair is denoted by o in the scheme. Hence, with the aid of the TAS-OSDS scheme, the IP of the signal transmitted by S_o and S_k can be formulated as

$$P_{\text{int\_}o}^{\text{OSDS}} = \Pr(C_{s_o d_o} < C_{s_m e}^m) \tag{25}$$

and

$$P_{\text{int\_}k}^{\text{OSDS}} = \Pr(C_{s_o d_o} < C_{s_m e}^k) \tag{26}$$

Using Eqs. (6) to (9), Eqs. (25) and (26) can be rewritten as

$$P_{\text{int\_}o}^{\text{OSDS}} = \Pr\left(\sum_{j=1}^{N_R} |h_{s_o d_{oj}}|^2 < \sum_{l=1}^{N_E} |h_{s_o e_l}|^2 \right) \tag{27}$$

and

$$P_{\text{int\_}k}^{\text{OSDS}} = \Pr\left(\sum_{j=1}^{N_R} |h_{s_o d_{o_j}}|^2 < \max\left(\sum_{l=1}^{N_E} |h_{s_o e_l}|^2, \frac{1}{\Lambda_1} \sum_{l=1}^{N_E} |h_{s_k e_l}|^2 \right) \right) \tag{28}$$

respectively, where $\Lambda_1 = P_t / P_s$. Based on Eq. (11), we can obtain

$$P_{\text{int\_}o}^{\text{OSDS}} = \Pr\left(\max_{m \in \Phi,\, 1 \leqslant i \leqslant N_T} \sum_{j=1}^{N_R} |h_{s_m d_{m_j}}|^2 < \sum_{l=1}^{N_E} |h_{s_m e_l}|^2 \right) \tag{29}$$

$$P_{\mathrm{int}\_k}^{\mathrm{OSDS}} = \Pr\Big(\max_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}}\sum_{j=1}^{N_{\mathrm{R}}} |h_{s_m d_{m_j}}|^2 < \max\Big(\sum_{l=1}^{N_{\mathrm{E}}} |h_{s_m e_l}|^2, \frac{1}{\Lambda_1}\sum_{l=1}^{N_{\mathrm{E}}} |h_{s_k e_l}|^2\Big)\Big) \tag{30}$$

Moreover, denoting $Q = \sum_{j=1}^{N_{\mathrm{R}}} |h_{s_m d_{m_j}}|^2$, $W_1 = \sum_{l=1}^{N_{\mathrm{E}}} |h_{s_m e_l}|^2$, and $W_2 = \sum_{l=1}^{N_{\mathrm{E}}} |h_{s_k e_l}|^2$, due to RVs Q, W_1 and W_2 being independent of each other, $P_{\mathrm{int}\_o}^{\mathrm{OSDS}}$ and $P_{\mathrm{int}\_k}^{\mathrm{OSDS}}$ can be formulated as

$$P_{\mathrm{int}\_o}^{\mathrm{OSDS}} = \Pr\Big(\max_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}}\sum_{j=1}^{N_{\mathrm{R}}} |h_{s_m d_{m_j}}|^2 < \sum_{l=1}^{N_{\mathrm{E}}} |h_{s_m e_l}|^2\Big) = \int_0^\infty \prod_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}} F_Q(w_1) f_{W_1}(w_1)\,\mathrm{d}w_1 \tag{31}$$

$$P_{\mathrm{int}\_k}^{\mathrm{OSDS}} = \Pr\Big(\max_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}}\sum_{j=1}^{N_{\mathrm{R}}} |h_{s_m d_{m_j}}|^2 < \max\Big(\sum_{l=1}^{N_{\mathrm{E}}} |h_{s_m e_l}|^2, \frac{1}{\Lambda_1}\sum_{l=1}^{N_{\mathrm{E}}} |h_{s_k e_l}|^2\Big)\Big) = \int_0^\infty\int_{w_2/\Lambda_1}^\infty \prod_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}} F_Q(w_1) f_{W_1}(w_1) f_{W_2}(w_2)\,\mathrm{d}w_1\mathrm{d}w_2 + \int_0^\infty\int_{\Lambda_1 w_1}^\infty \prod_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}} F_Q\Big(\frac{w_2}{\Lambda_1}\Big) f_{W_2}(w_2) f_{W_1}(w_1)\,\mathrm{d}w_2\mathrm{d}w_1 \tag{32}$$

Based on Ref. [10], $F_Q(w)$, $f_{W_1}(w_1)$ and $f_{W_2}(w_2)$ can be given as

$$F_Q(w_1) = 1 - \exp\Big(-\frac{w_1}{\sigma_{md}^2}\Big)\sum_{l=0}^{N_{\mathrm{R}}-1}\frac{1}{l!}\Big(\frac{w_1}{\sigma_{md}^2}\Big)^l \tag{33}$$

$$f_{W_1}(w_1) = \frac{w_1^{N_{\mathrm{E}}-1}}{(N_E-1)!}\Big(\frac{1}{\sigma_{me}^2}\Big)^{N_{\mathrm{E}}}\exp\Big(-\frac{w_1}{\sigma_{me}^2}\Big) \tag{34}$$

$$f_{W_2}(w_2) = \frac{w_2^{N_{\mathrm{E}}-1}}{(N_{\mathrm{E}}-1)!}\Big(\frac{1}{\sigma_{me}^2}\Big)^{N_{\mathrm{E}}}\exp\Big(-\frac{w_2}{\sigma_{me}^2}\Big) \tag{35}$$

Using Ref. [11] and substituting Eqs. (33) and (34) into Eq. (31) yields

$$P_{\mathrm{int}\_o}^{\mathrm{OSDS}} = \int_0^\infty \prod_{m\in\Phi,\,1\leqslant i\leqslant N_{\mathrm{T}}} F_Q(w_1) f_{W_1}(w_1)\,\mathrm{d}w_1 = \sum_S \int_0^\infty \Psi_0 w_1^{\beta_2+N_{\mathrm{E}}-1}\exp\Big(-\frac{w_1}{\sigma_{me}^2}-\beta_3 w_1\Big)\mathrm{d}w_1 = \sum_S \Psi_0(\beta_2+N_{\mathrm{E}}-1)!\Big(\frac{1}{\sigma_{me}^2}+\beta_3\Big)^{-\beta_2-N_{\mathrm{E}}} \tag{36}$$

where $\beta_1 = \dfrac{(|\Phi|N_{\mathrm{T}})!}{\prod_{i=1}^{N_{\mathrm{R}}+1} n_i!}\prod_{j=1}^{N_{\mathrm{R}}}\Big(-\dfrac{1}{\sigma_{md}^{2(j-1)}(j-1)!}\Big)^{n_j}$, $\beta_2 = \sum_{j=1}^{N_{\mathrm{R}}} n_j(j-1)$, $\beta_3 = \dfrac{1}{\sigma_{md}^2}(|\Phi|N_{\mathrm{T}} - n_{N_{\mathrm{R}}+1})$, $S = \Big\{(n_1, n_2, \ldots, n_{N_R+1}) \,\Big|\, \sum_{i=1}^{N_{\mathrm{R}}+1} n_i = |\Phi|N_{\mathrm{T}}\Big\}$, and $\Psi_0 = \dfrac{\beta_1}{(N_{\mathrm{E}}-1)!}\Big(\dfrac{1}{\sigma_{me}^2}\Big)^{N_{\mathrm{E}}}$.

Using Eqs. (33), (34) and (35), Eq. (32) can be obtained as

$$P_{\mathrm{int}\_k}^{\mathrm{OSDS}} = \sum_S\sum_{t=0}^{\beta_2+N_{\mathrm{E}}-1} a_{\beta p}c_{\beta d}\Big(\frac{d'_{km}}{\Lambda_1}+\frac{\beta_3}{\Lambda_1}\Big)^{-t-N_{\mathrm{E}}} + \sum_S\sum_{t=0}^{\beta_2+N_{\mathrm{E}}-1} a_{\beta p}d_{\beta d}(c'_{km}\Lambda_1+\beta_3)^{-t-N_{\mathrm{E}}} \tag{37}$$

where $a_{\beta p} = \dfrac{\Big(\frac{1}{\sigma_{me}^2}\Big)^{N_{\mathrm{E}}}\Big(\frac{1}{\sigma_{me}^2}\Big)^{N_{\mathrm{E}}}\beta_1}{t!(N_{\mathrm{E}}-1)!(N_{\mathrm{E}}-1)!}$, $c_{\beta d} = \Big(\dfrac{1}{\sigma_{me}^2}+\beta_3\Big)^{-\beta_2-N_{\mathrm{E}}+t}\Lambda_1^{-t}(\beta_2+N_{\mathrm{E}}-1)!(t+N_{\mathrm{E}}-1)!$, $c'_{km} = \dfrac{1}{\sigma_{me}^2}+\dfrac{1}{\Lambda_1\sigma_{me}^2}$, $d'_{km} = \dfrac{\Lambda_1}{\sigma_{me}^2}+\dfrac{1}{\sigma_{me}^2}$, and $d_{\beta d} = \Big(\dfrac{1}{\sigma_{me}^2}+\dfrac{\beta_3}{\Lambda_1}\Big)^{-\beta_2-N_{\mathrm{E}}+t}\Lambda_1^{t-\beta_2}(t+N_{\mathrm{E}}-1)!(\beta_2+N_{\mathrm{E}}-1)!$.

Then, with the aid of the definition in Eq. (23), the IP of the multiple SD pairs aided by the proposed TAS-OSDS scheme can be given by

$$P_{\mathrm{int}}^{\mathrm{OSDS}} = \frac{1}{M}\Big(\sum_{k\in\Phi-\{i\}} P_{\mathrm{int}\_k}^{\mathrm{OSDS}} + P_{\mathrm{int}\_o}^{\mathrm{OSDS}}\Big) \tag{38}$$

From Eq. (38), we can not only evaluate the PLS of wireless transmissions, but also investigate the effects of the channel gain, the number of antennas, and the number of source-destination (SD) pairs on the attainable PLS level of wireless transmissions.

3 Numerical Results

In this section, we evaluate the IP of the proposed TAS-OSDS by comparing this scheme with the conventional RSDS scheme. In this evaluation, the analytic IP of the RSDS and TAS-OSDS schemes are evaluated by plotting Eq. (24) and Eq. (38), respectively. Moreover, we assume that the main-to-eavesdropper ratio (MER) $\lambda_{se} = \sigma_{md}^2/\sigma_{me}^2$. For comparison purposes, the traditional non-cooperation (non-coop) transmission scheme is also presented, wherein the SD pairs work independently. For the sake of fair comparison of the above mentioned schemes, we assume that each pair only occupies $1/M$ times bandwidth of the whole spectrum. In contrast, the transmission SD pair can occupy the total shared spectrum due to only one SD pair being selected to perform transmission at the given transmission slot in the investigated cooperative method. Hence, the IP of the non-coop scheme is shown as

$$P_{\mathrm{int}}^{\mathrm{Non}} = \frac{1}{M}\sum_{m=1}^{M}\Pr\Big(\max_i\sum_{j=1}^{N_{\mathrm{R}}} |h_{s_m d_{m_j}}|^2 < \sum_{l=1}^{N_{\mathrm{E}}} |h_{s_m e_l}|^2\Big) \tag{39}$$

Similarly to Eq. (36), $P_{\mathrm{int}}^{\mathrm{Non}}$ can be obtained as

$$P_{\rm int}^{\rm Non}=\frac{1}{M}\sum_{m=1}^{M}\int_0^{\infty}\prod_{1\leqslant i\leqslant N_{\rm T}}F_Q(w_1)f_{W_1}(w_1)\,{\rm d}w_1=\frac{1}{M}\sum_{m=1}^{M}\sum_{S'}\int_0^{\infty}\Psi'_0 w_1^{\beta'_2+N_{\rm E}-1}\exp\left(-\frac{w_1}{\sigma_{me}^2}-\beta'_3 w_1\right){\rm d}w_1=\frac{1}{M}\sum_{m=1}^{M}\sum_{S'}\Psi'_0(\beta'_2+N_{\rm E}-1)!\left(\frac{1}{\sigma_{me}^2}+\beta'_3\right)^{-\beta'_2-N_{\rm E}} \tag{40}$$

where $\beta'_1=\frac{(N_{\rm T})!}{\prod_{i=1}^{N_{\rm R}+1}n_i!}\prod_{j=1}^{N_{\rm R}}\left(-\frac{1}{\sigma_{md}^{2(j-1)}(j-1)!}\right)^{n_j}$, $\beta'_2=\sum_{j=1}^{N_{\rm R}}n_j(j-1)$, $\beta'_3=\frac{1}{\sigma_{md}^2}(N_{\rm T}-n_{N_{\rm R}+1})$, $S'=\left\{(n_1,n_2,\ldots,n_{N_{\rm R}+1})\;\middle|\;\sum_{i=1}^{N_{\rm R}+1}n_i=N_{\rm T}\right\}$, and $\Psi'_0=\frac{\beta'_1}{(N_{\rm E}-1)!}\left(\frac{1}{\sigma_{me}^2}\right)^{N_{\rm E}}$.

Fig. 2 shows the IP vs. MER of the traditional RSDS, non-coop as well as of the proposed TAS-OSDS schemes for different ($N_{\rm T}$, $N_{\rm R}$, $N_{\rm E}$) by plotting Eq. (24), Eq. (40) and Eq. (38), as a function of the MER. It is shown in Fig. 2 that as the number of antennas ($N_{\rm T}$, $N_{\rm R}$, $N_{\rm E}$) increases from ($N_{\rm T}$, $N_{\rm R}$, $N_{\rm E}$) = (1, 1, 1) to (2, 2, 2), the IP of the RSDS, non-coop and TAS-OSDS schemes will be reduced correspondingly, which confirms that the PLS of wireless transmissions can be enhanced by increasing the number of antennas of the SD pairs. Moreover, Fig. 2 also shows that although the IP of all schemes will be decreased as the MER increases from −10 to 15 dB, the proposed TAS-OSDS schemes can still achieve the lowest IP among the RSDS, non-coop, and TAS-OSDS schemes. Hence, at a given IP constraint, the proposed TAS-OSDS scheme can be used to guarantee the PLS of wireless transmission in a lower MER case.

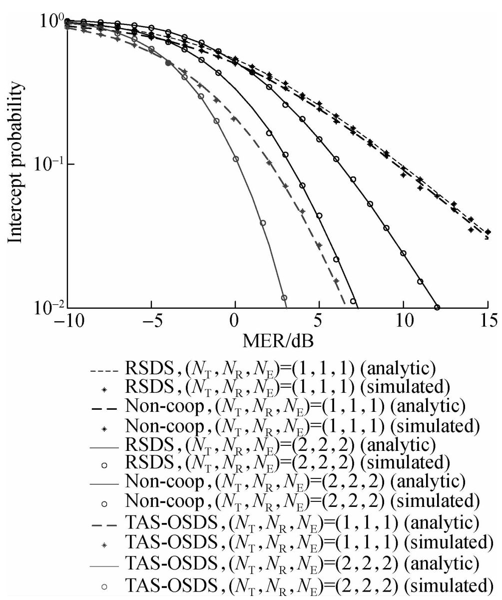

Fig. 2 Comparison of intercept probabilities under different MERs

Fig. 3 illustrates the IP vs. the number of source-destination pairs M of the traditional RSDS, non-coop and the TAS-OSDS schemes for different numbers of antennas of E. As shown in Fig. 3, increasing the number of antennas of E will increase the risk of the wireless transmission being eavesdropped upon successfully in the traditional RSDS, non-coop and the TAS-OSDS schemes, whereas the IP of the TAS-OSDS is lower than that of both the RSDS and non-coop schemes. Furthermore, it can be seen from Fig. 3 that although the PLS of wireless transmissions will be degraded, the IP of wireless transmissions will be significantly decreased relying on increasing the number of SD pairs in the proposed scheme, demonstrating the superiority of the proposed TAS-OSDS scheme. This is due to the fact that the cooperation between SD pairs will be more beneficial for increasing the PLS of wireless transmissions in the proposed TAS-OSDS scheme, whereas no benefit can be achieved in either the RSDS or non-coop schemes.

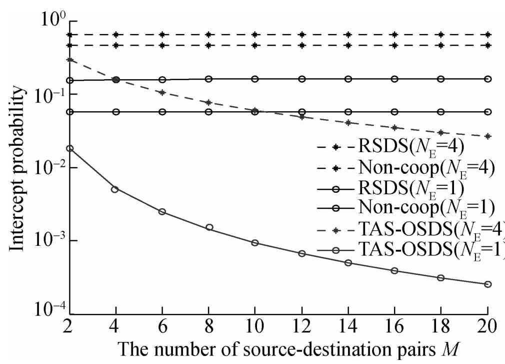

Fig. 3 Intercept probability with respect to the number of SD pairs M

4 Conclusion

1) In this paper, we study PLS for a heterogeneous wireless network including multiple SD pairs in the presence of an eavesdropper, where the SD pairs access the shared spectrum in a dynamic manner.

2) We explore a cooperation framework for SD pairs to protect against eavesdropping attacks. Specifically, an SD pair is chosen as the transmitting pair at the beginning of the given transmission slot, then it participates in collaborative transmitting among the SD pairs. Moreover, the IPs of the proposed TAS-OSDS as well as the conventional RSDS schemes are analyzed for comparison purposes.

3) It is shown that the TAS-OSDS scheme achieves a better IP performance than that of the RSDS and conventional non-cooperation schemes, where each source communicates with its corresponding destination without cooperating with other SD pairs in the non-cooperation scheme. Furthermore, with an increasing number of the SD pairs, the IP of the TAS-OSDS scheme will be reduced clearly.

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无线异构网络中基于传输节点对调度的物理层安全增强方法

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摘要:为了增强无线异构网络中数据传输的物理层安全性能,采用了一个基于两阶段传输的协作框架.在传输时隙开始时,一个源节点-目的节点对将会被机会式选择,并被用于辅助其他源节点-目的节点对传输数据.在该协作框架下,提出了一种发射天线选择辅助的源节点-目的节点对调度方案,并分析了该方案、传统源节点-目的节点对轮询调度方案及传统非协作方案的窃听概率,其中传统轮询调度方案和非协作方案被用于与所提发射天线选择辅助的源节点-目的节点调度方案进行对比.数值结果表明,增加源节点-目的节点对的数量可以有效降低所提方案的窃听概率,而传统轮询调度方案和非合作方案的窃听概率随着源节点-目的节点对数量的增加而没有变化.此外,所提方案能够比轮询调度方案和非合作方案取得更低的窃听概率,显示了所提方案的优越性.

关键词:无线异构网络;物理层安全;源-目的节点对调度

中图分类号:TN929.5