Secure Full Duplex Communications in the Presence of Malicious Adversary

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***Abstract*—In this paper, we study the physical layer security in the presence of an adversary which is able to switch its mode from jamming mode (when transmits jamming signals) to eavesdropping mode (when adversary eavesdrops legitimate link) and vice versa. To combat with this type of adversary and establish security in this communication, we propose two approaches: 1) probabilistic approach (PA), 2) worst case approach (WCA). The system model consists of a source, an adversary and full-duplex destination. A full-duplex destination can receive the private message and transmit jamming signal to deceive the adversary, simultaneously. The simulation results show that the average rate PA, is 50% more than the WCA.**

***Index Terms*—Cooperative communications, power allocation, mode switching of adversary, full-duplex destination.**

I. Introduction

DUE to the broadcast nature of wireless communication, all nodes within the communication range can receive signals, this issue implies that wireless communication vulnerable to eavesdropping. To this end, traditionally security in wireless communication has been performed in upper layers by cryptographic methods. These methods are based on sharing a key between legitimate source and legitimate destination [1]. Due to the high complexity of key management, recently physical layer security in information theory viewpoint has been attracted a lot of attention, [2]. It is demonstrated in [3], when the legitimate destination rate is higher than the adversary rate secure transmission happens in information theory viewpoint.

The cooperative jamming is an approach for increasing security, in which the users or relays nodes transmit jamming signals to decrease the adversary rate [4]. In [5], the authors use one helper, which is able to increase achievable secrecy rate via relaying or confuse eavesdropper by jamming. The full-duplex destination strategy has been utilized in many works e.g., [6] and [7]. In this strategy, destination can transmit jamming signals to mislead the adversary while it's receiving private message from the source on the same frequency band, hence this work reduces the cost of purchasing jamming station.

We assume that the malicious adversary has the ability to switch between two modes, in the first mode which is called eavesdropping, adversary tries to eavesdrop the legitimate link and in the second mode which is called jamming, adversary transmits artificial noise (jamming) to mislead the destination. To tackle this issue, two approaches are proposed called probabilistic approach (PA), and worst case approach (WCA). In the PA, we consider probability of two modes, thus the adversary is in the jamming and eavesdropping mode with probability P, and $1-P$, respectively. In the WCA, we consider the worst case secrecy rate between jamming and eavesdropping modes. Note that the WCA firstly investigated in [8], and we apply this method in our system model, while the PA is completely new approach and has not been investigated yet.

II. System Model and Problem Formulation

We consider a communication scenario with a legitimate source, a legitimate destination and a malicious adversary. As depicted in Fig. 1, in this scenario, we assume that the destination is full duplex and bidirectional communication occurs i.e., the destination transmits jamming and receives private messages on the same time and frequency band. Nodes of source and destination are equipped with single and two antennas, respectively.

Source and destination transmit symbols x and j_d, respectively. The received signal at destination and adversary, when the adversary is in the eavesdropping mode, are written as follows [10]:

$$y_{de} = \sqrt{p_s} h_{sd} x + \xi \sqrt{p_{jd}} h_{dd} j_d + n_d, \tag{1}$$

$$y_e = \sqrt{p_s} h_{sa} x + \sqrt{p_{jd}} h_{ad} j_d + n_e, \tag{2}$$

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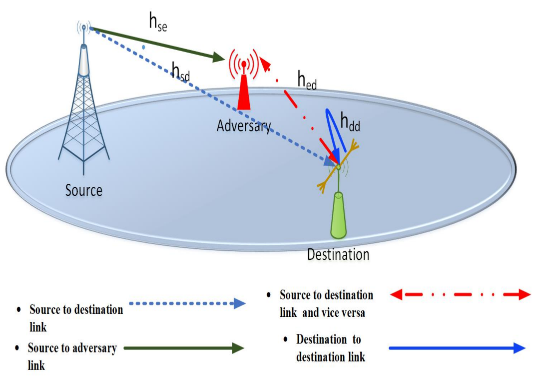

Fig. 1. System model.

respectively. When adversary is in the jamming mode, the received signal at the destination is given by [10]:

$$y_{dj} = \sqrt{p_s} h_{sd} x + \sqrt{p_{ja}} h_{ad} j_e + \xi \sqrt{p_{jd}} h_{dd} j_d + n_d, \quad (3)$$

where p_s is the allocated transmit power to the source. p_{jd} is the allocated jamming power to the destination for deceiving adversary, and ξ is defined as a self interference cancellation coefficient, $0 < \xi < 1$. p_{ja} is the jamming power of adversary. h_{sd}, h_{sa} and h_{ad} are the channel coefficients between, source and destination, source and adversary, adversary and destination, respectively also the self interference channel coefficient at destination is denoted by h_{dd}. y_{de} and y_{dj} are the received signals at the destination in the eavesdropping and jamming modes, respectively. n_d and n_e are white Gaussian noise with zero-mean and variances σ_d^2 and σ_e^2, respectively.

When the adversary is in the eavesdropping mode, the achievable secrecy rate can be written as [10]:

$$R_{se} = \max\{\log\left(1 + \frac{p_s|h_{sd}|^2}{\sigma_d^2 + \xi^2 p_{jd}|h_{dd}|^2}\right) - \log\left(1 + \frac{p_s|h_{sa}|^2}{\sigma_e^2 + p_{jd}|h_{ad}|^2}\right), 0\}, \quad (4)$$

and when the adversary is in the jamming mode, the achievable rate is [10]:

$$R_{sj} = \log\left(1 + \frac{p_s|h_{sd}|^2}{\sigma_d^2 + p_{ja}|h_{ad}|^2 + \xi^2 p_{jd}|h_{dd}|^2}\right). \quad (5)$$

A. Probabilistic Approach

In this scenario, we assume that, all channels experience block fading, i.e., the values of channel coefficients are constant during a block of transmission and for the next block changes independently.

All channels are assumed undergo Rayleigh fading with zero mean and one variance, hence the channel power gains have exponential distribution with parameters $\frac{\omega_{sd}}{2}$, $\frac{\omega_{sa}}{2}$, $\frac{\omega_{ad}}{2}$ and $\frac{\omega_{dd}}{2}$, where $\omega_{sd} = \omega_{sa} = \omega_{ad} = \omega_{dd} = 1$, for example

$$f_{|h_{sd}|^2}\left(|h_{sd}|^2\right) = \frac{\omega_{sd}}{2} e^{-\frac{\omega_{sd}}{2}|h_{sd}|^2}. \quad (6)$$

To address the mentioned challenge, we consider average rate as follows:

$$\begin{aligned} r^L = \; & R_{sj}\mathbb{P}\{\text{adversary is in jamming mode}\} + \\ & R_{se}\mathbb{P}\{\text{adversary is in eavesdropping mode}\}, \end{aligned} \quad (7)$$

where $\mathbb{P}\{x\}$ is defined as the probability of event x. Therefore we have:

$$r^L = R_{sj}\mathbb{P}\{\rho > 0\} + R_{se}\mathbb{P}\{\rho \le 0\}, \quad (8)$$

where ρ is expressed as:

$$\rho = \log\left(1 + \frac{p_s|h_{sd}|^2}{\sigma_d^2 + \xi^2 p_{jd}|h_{dd}|^2}\right) - \log\left(1 + \frac{p_s|h_{sa}|^2}{\sigma_e^2 + p_{jd}|h_{ad}|^2}\right). \quad (9)$$

This benchmark is optimal for adversary, because when $\rho \le 0$ ($R_{se} = 0$), transmission is insecure based on the physical layer security theory, hence the adversary can eavesdrop the private message. More over, if $\rho > 0$ ($R_{se} > 0$), transmission is secure based on the physical layer security theory, in this situation adversary transmits jamming signals because eavesdropping is not useful for it. The transmitter aims to maximize r^L under power limitation, i.e., it solves the following optimization problem

$$\begin{aligned} & \max_{p_s, p_{jd}} r^L, \\ & \text{s.t}: \quad p_s \le p_s^{\max}, \\ & \qquad\quad p_{jd} \le p_{jd}^{\max}, \end{aligned} \quad (10)$$

where $p_s^{\max}$ is the maximum allowable transmit power of source, as well as $p_{jd}^{\max}$ is the maximum allowable transmit power of destination.

We can write $\mathbb{P}\{\rho \ge 0\}$ as:

$$\mathbb{P}\{\rho \ge 0\} = \frac{e^{\frac{\xi^2+1}{2\xi^2 p_{jd}}}}{4\xi^2} \int_{\frac{1}{p_{jd}}}^{\infty} \int_{\frac{1}{p_{jd}}}^{\infty} \frac{u}{z+u} e^{-\left(\frac{\xi^2 z + u}{2\xi^2}\right)} dz du. \quad (11)$$

proof: See Appendix A. ■

B. Worst Case Approach

In this approach, the worst case rate is written as

$$R_s = \min(R_{sj}, R_{se}), \tag{12}$$

let $\mathbf{P}_{jd}^T = \left[p_{jd}^1, ..., p_{jd}^T\right]$ and $\mathbf{P}_s^T = \left[p_s^1, ..., p_s^T\right]$, are the power allocation vectors. Time averaged achievable rate of the destination is defined as [14]

$$R_T = \frac{1}{T}\sum_{t=1}^{T} \min(R_{sj}^t, R_{se}^t), \tag{13}$$

where T is the length of averaging time window. Therefore, the optimization problem with the power limitations is formulated as

$$\max_{\mathbf{P}_s^T, \mathbf{P}_{jd}^T} \frac{1}{T}\sum_{t=1}^{T} \min(R_{sj}^t, R_{se}^t), \tag{14}$$

$$\begin{aligned} \text{s.t}: \quad & \mathbf{P}_s^T \preceq \mathbf{P}_s^{\max}, \\ & \mathbf{P}_{jd}^T \preceq \mathbf{P}_{jd}^{\max}, \end{aligned} \tag{15}$$

III. OPTIMIZATION PROBLEM SOLUTION

In this section, we present the solution of both PA and WCA optimization problems, that are explained in (10) and (14), respectively.

A. PA Problem Solution

By using the epigraph method [15], and introducing auxiliary variable $w = \max\{\rho, 0\}$, and replacing (11) in (8), we have:

$$\begin{aligned} \max_{p_s, p_{jd}} \ & r^L, \\ \text{s.t}: \quad & p_s \leq p_s^{\max}, \\ & p_{jd} \leq p_{jd}^{\max}, \\ & w \geq \rho, \\ & w \geq 0, \end{aligned} \tag{16}$$

where

$$r^L = \left(\frac{e^{\frac{\xi^2+1}{2\xi^2 p_{jd}}}}{4\xi^2} \int_{\frac{1}{p_{jd}}}^{\infty} \int_{\frac{1}{p_{jd}}}^{\infty} \frac{u}{z+u} e^{-\left(\frac{\xi^2 z+u}{2\xi^2}\right)} dz du \right) \times \tag{17}$$

$$(w - R_{sj}) + R_{sj}, \tag{18}$$

by calculating the Hessian matrix, non convexity of problem (10) can be proved easily. In order to solve the problem (10) and find a near optimal solution, we adopt the dual Lagrange method, as follows:

$$\begin{aligned} & L\left(p_s, p_{jd}, \alpha, \beta\right) = r^L + \mu\left(w - \rho\right) + \eta w + \\ & \alpha\left(p_s^{\max} - p_s\right) + \beta\left(p_{jd}^{\max} - p_{jd}\right). \end{aligned} \tag{19}$$

Algorithm 1 The algorithm for solving proposed optimization problem

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1: Initialization: Initialize the Lagrangian multipliers, i.e., $\alpha\left(0\right)$, $\beta\left(0\right)$ and $\xi\left(0\right)$.,
2: Find the values of p_s andp_{jd} at each iteration by setting derivative of Lagrange function, with respect to the optimization variables, equal to zero,
3: Update the Lagrange multipliers, i.e., $\alpha\left(n\right), \beta\left(n\right)$ and $\xi\left(n\right)$,
4: If the stopping condition is satisfied i.e., $p_s(n) - p_s(n-1) < \epsilon$ and $p_{jd}(n) - p_{jd}(n-1) < \epsilon$ go to step 5, otherwise go to step 2,
5: stop, return p_s and p_{jd}

We take the derivative of Lagrange function, (19), with respect to the optimization variables, then set them equal to zero. For example the derivative of Lagrange function with respect to p_s can be written as follows:

$$\begin{aligned} & \frac{\partial L(.)}{\partial p_s} = -\alpha - \mu\frac{1}{\ln(2)}\left(\frac{|h_{sd}|^2}{\left(\sigma_d^2 + p_s|h_{sd}|^2 + \xi^2 p_{jd}|h_{dd}|^2\right)}\right. \\ & \left. - \frac{|h_{sa}|^2}{\left(\sigma_e^2 + p_{jd}|h_{ad}|^2 + p_s|h_{sa}|^2\right)}\right) + \\ & \frac{1}{\ln(2)}\frac{|h_{sd}|^2}{\left(\sigma_d^2 + p_{ja}|h_{ad}|^2 + p_s|h_{sd}|^2 + \xi^2 p_{jd}|h_{dd}|^2\right)} \times \\ & \quad 1 - \frac{e^{\frac{\xi^2+1}{2\xi^2 p_{jd}}}}{4\xi^2} \int_{\frac{1}{p_{jd}}}^{\infty} \int_{\frac{1}{p_{jd}}}^{\infty} \frac{u}{z+u} e^{-\left(\frac{\xi^2 z+u}{2\xi^2}\right)} dz du \Bigg) = 0. \end{aligned} \tag{20}$$

The optimal values of auxiliary variables w is given by [8]:

$$w = \begin{cases} 0 & \mu + \eta < 0, \\ \infty & \mu + \eta > 0, \\ Any & \mu + \eta = 0. \end{cases} \tag{21}$$

We use subgradient approach for solving optimization problem. At iteration n^{th}, Lagrange multipliers, α, β and ζ are updated for example as follows [15],

$$\alpha\left(n\right) = \left[\alpha\left(n-1\right) - \delta\left(p_s^{\max} - p_s\right)\right]^+, \tag{22}$$

where δ is an update step for Lagrange multipliers and $[x]^+ = \max(x, 0)$. The iterative algorithms is shown in Table. I.

B. WCA Problem Solution

We define the auxiliary variables r^t and q^t to reformulate (14) as follows:

$$\max_{\mathbf{P}_s^T, \mathbf{P}_{jd}^T, \mathbf{r}, \mathbf{q}} \frac{1}{T} \sum_{t=1}^{T} r^t, \tag{23}$$

$$\begin{aligned}
\text{s.t} : \ & P_s^t \leq P_s^{\max}, \forall t \\
& P_{jd}^t \leq P_{jd}^{\max}, \forall t \\
& q^t \geq \log \left(1 + \frac{p_s^t |h_{sd}|^2}{\sigma_d^2 + p_{jd}^t |h_{dd}|^2} \right) - \qquad (24) \\
& \qquad \log \left(1 + \frac{p_s^t |h_{sa}|^2}{\sigma_e^2 + p_{jd}^t |h_{ad}|^2} \right) \forall t \qquad (25) \\
& q^t \geq 0, \forall t \\
& r^t \leq \log \left(1 + \frac{p_s^t |h_{sd}|^2}{\sigma_d^2 + p_{ja} |h_{ad}|^2 + p_{jd}^t |h_{dd}|^2} \right), \forall t \\
& r^t \leq q^t, \forall t.
\end{aligned}$$

Problem (23) is a non-convex optimization problem, in order to solve this problem, and find a near optimal solution, we use the dual Lagrange method as follows:

$$\begin{aligned}
& L \left(p_s^t, p_{jd}^t, p_s^t, \alpha, \beta, \psi, \theta, \omega, \varphi \right) = \tfrac{1}{T} \sum_{t=1}^{T} r^t + \\
& \sum_{t=1}^{T} \left(\alpha_t \left(p_s^{\max} - p_s^t \right) + \beta_t \left(p_{jd}^{\max} - p_{jd}^t \right) + \right. \\
& \psi_t \left(q^t - \log \left(\frac{1 + \frac{p_s^t |h_{sd}|^2}{\sigma_d^2 + p_{jd}^t |h_{dd}|^2}}{1 + \frac{p_s^t |h_{sa}|^2}{\sigma_e^2 + p_{jd}^t |h_{ad}|^2}} \right) \right) + \theta_t \left(q^t \right) + \\
& \omega_t \left(\log \left(1 + \frac{p_s^t |h_{sd}|^2}{\sigma_d^2 + p_{ja} |h_{ad}|^2 + p_{jd}^t |h_{dd}|^2} \right) - r^t \right) \\
& \left. \varphi_t \left(q^t - r^t \right) . \right.
\end{aligned} \tag{26}$$

We take derivative of Lagrange function, (26), with respect to the optimization variables, then set them equal to zero, also for obtaining optimal values of auxiliary variables, we take derivative of Lagrange function, (26), with respect to r^t and q^t as follows:

$$\frac{dL(.)}{dr^t} = \frac{1}{T} - \omega_t - \varphi_t, \tag{27a}$$

$$\frac{dL(.)}{dq^t} = \psi_t + \theta_t + \varphi_t, \tag{27b}$$

we have:

$$\frac{dL(.)}{dr^t} = \begin{cases} < 0 & \frac{1}{T} < \omega_t + \varphi_t, \\ = 0 & \frac{1}{T} = \omega_t + \varphi_t, \\ > 0 & \frac{1}{T} > \omega_t + \varphi_t, \end{cases} \tag{28a}$$

$$\frac{dL(.)}{dq^t} = \begin{cases} < 0 & \psi_t + \theta_t + \varphi_t < 0, \\ = 0 & \psi_t + \theta_t + \varphi_t = 0, \\ > 0 & \psi_t + \theta_t + \varphi_t > 0, \end{cases} \tag{28b}$$

the optimal values of auxiliary variables are given by [8]:

$$r^t = \begin{cases} 0 & \frac{1}{T} < \omega_t + \varphi_t, \\ \infty & \frac{1}{T} = \omega_t + \varphi_t, \\ Any & \frac{1}{T} > \omega_t + \varphi_t, \end{cases} \tag{29a}$$

$$q^t = \begin{cases} 0 & \psi_t + \theta_t + \varphi_t < 0, \\ \infty & \psi_t + \theta_t + \varphi_t > 0, \\ Any & \psi_t + \theta_t + \varphi_t = 0, \end{cases} \tag{29b}$$

where we use an iterative algorithm similar to Table. I, i.e., Step1: Initialize the Lagrangian multipliers. Step2: Find the values of optimization variables (by setting derivative of Lagrange function, (26), with respect to the optimization variables, equal to zero). Step3: Update the auxiliary variables r^t and q^t, (29). Step4: Update the Lagrange multipliers. Step5: If the stopping condition is satisfied, go to step 6, otherwise go to step 2. Step6: End.

IV. SIMULATION RESULTS

In this section, we present simulation results and evaluate the performance of two proposed approaches. For simplicity, we assume that the variances of all channels are equal to one, i.e., $\sigma_d^2 = \sigma_e^2 = 1$. In this section we assume $p_s^{\max}$ and $p_{jd}^{\max}$ are 4 Watt and p_{ja} is 0.5 Watt.

Fig. 2, compares our proposed solution with the optimal solution (computed by exhaustive search method), when $\xi = 0$, i.e., the self interference is canceled perfectly. As can be seen, there is only 11.59% gap between the exhaustive search and proposed solution. Also this

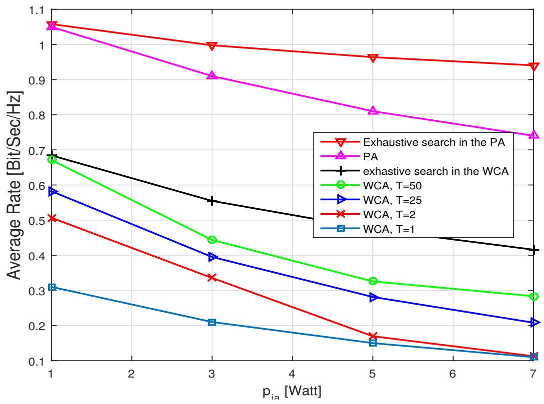

Fig. 2. Average rate *vs*. jamming power of adversary, and comparison between PA and WCA, for $\xi = 0$.

figure compares average rate obtained by applying the PA and WCA methods. As depicted in this figure, for all values of p_{ja}, the average rate obtained by the PA is more than that obtained by WCA. In addition, as can be seen in this figure, the average rate increases by increasing T, because by increasing the size of observation window, the duality gap is decreased, corresponds to Theorem 1 in [14]. Note that for obtaining the percentage of gap between the exhaustive search method and proposed solution, first we calculated percentage of gap between the exhaustive search and proposed solution in a limited number of points then we averaged them.

In Fig. 3, the average rate obtained by PA and WCA are presented, in the case of $\xi = 1$, i,.e, when the self interference is not canceled. In this situation, average rate in the PA is more than WCA, too. As depicted in this figure, the gap between the exhaustive search and proposed solution is only 5.1% in the PA. In Fig. 4, we show the impact of self interference cancellation coefficient on the average rate, when $p_{ja} = 0.5$ Watt. This figure demonstrates that for $\xi = 0$ the gap between PA and WCA is more than the gap between PA and WCA for $\xi = 1$.

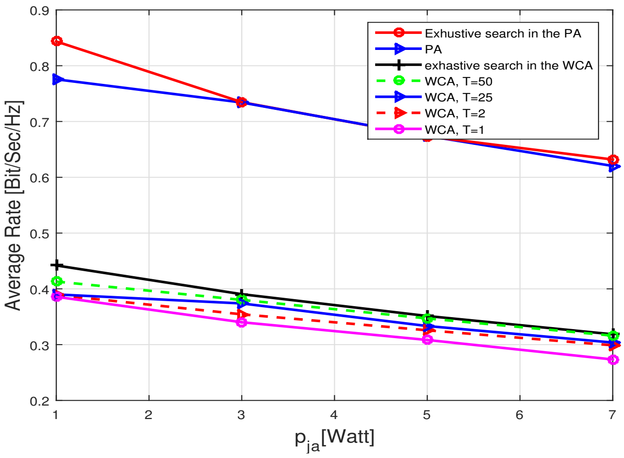

Fig. 3. Average rate *vs*. jamming power of adversary, comparison PA and WCA, for $\xi = 1$.

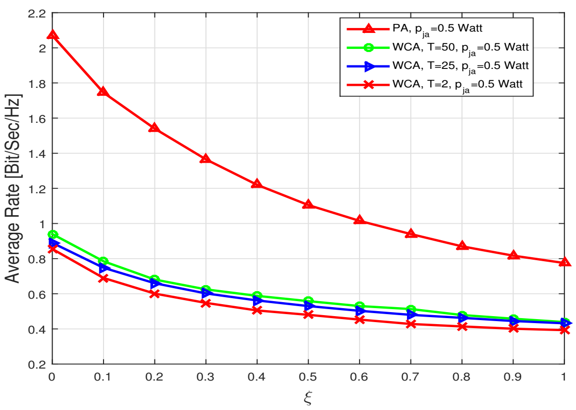

Fig. 4. Average rate *vs*. self interference cancellation coefficient.

V. CONCLUSION

In this paper, physical layer security was investigated in cooperative network. Full-duplex destination receives message and transmits jamming simultaneously. The adversary is able to switch its mode, (eavesdropping and jamming) to minimize the average rate.

To combat with this type of adversary and establish security in this communication, we propose two novel approaches: 1) PA, 2) WCA. In the PA, we presented power allocation, based on the probability of switching, while the goal of WCA, is to maximize the worst rate. Simulation results are shown that PA average rate is 50% more that of the WCA. In the WCA, the average rate increases by increasing the length of averaging time window (T). As well, in fact duality gap is reduced, by increasing T.

APPENDIX A
PROOF OF EQUATION (11)

$$\mathbb{P}\left\{\rho > 0\right\} = \left\{\log\left(\frac{1+\frac{p_s|h_{sd}|^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2}}{1+\frac{p_s|h_{sa}|^2}{\sigma_e^2+p_{jd}|h_{ad}|^2}}\right) > 0\right\}, \quad (31)$$

$$= \mathbb{P}\left\{1+\frac{p_s|h_{sd}|^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2} > 1+\frac{p_s|h_{sa}|^2}{\sigma_e^2+p_{jd}|h_{ad}|^2}\right\},$$

$$= \mathbb{P}\left\{\frac{p_s|h_{sd}|^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2} > \frac{p_s|h_{sa}|^2}{\sigma_e^2+p_{jd}|h_{ad}|^2}\right\},$$

$$= \mathbb{P}\left\{\frac{|h_{sd}|^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2} > \frac{|h_{sa}|^2}{\sigma_e^2+p_{jd}|h_{ad}|^2}\right\} =$$

$$\mathbb{P}\left\{\frac{|h_{sd}|^2\sigma_e^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2} + \frac{p_{jd}|h_{ad}|^2|h_{sd}|^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2} > |h_{sa}|^2\right\} =$$

$$-\mathbb{P}\left\{|h_{sa}|^2 > \frac{|h_{sd}|^2\sigma_e^2}{\sigma_d^2+\xi^2 p_{jd}|h_{dd}|^2} + \frac{p_{jd}|h_{ad}|^2|h_{sd}|^2}{\sigma_d^2+p_{jd}|\xi^2 h_{dd}|^2}\right\}$$

$$+1.$$

For simplicity, it is assumed that the variances of all channels are equal to one, and the channel power gains have exponential distribution, then we have (30). We define new variables $u = \frac{1+p_{jd}|h_{dd}|^2}{p_{jd}}$ p_{jd} 2 to simplify (30c) as follows:

$$\mathbb{P}\left\{\rho \leq 0\right\} = \quad (32)$$

$$\frac{e^{\frac{\xi^2+1}{2\xi^2 p_{jd}}}}{4\xi^2}\int_{\frac{1}{p_{jd}}}^{\infty}\int_{\frac{1}{p_{jd}}}^{\infty} \frac{u}{z+u} e^{-\frac{2\xi^2}{\xi^2 z+u}}\Big) dzdu.$$

$$\mathbb{P}\left\{\rho \leq 0\right\} = \int_0^{\infty} \int_0^{\infty} \int_{\frac{|h_{sd}|^2\left(1+p_{jd}|h_{ad}|^2\right)}{1+\xi^2 p_{jd}|h_{dd}|^2}}^{\infty} f_{|h_{sa}|^2}\left(|h_{sa}|^2\right) f_{|h_{sd}|^2}\left(|h_{sd}|^2\right) f_{|h_{ad}|^2}\left(|h_{ad}|^2\right) \tag{30a}$$

$$f_{|h_{dd}|^2}\left(|h_{dd}|^2\right) d\left(|h_{sa}|^2\right) d\left(|h_{sd}|^2\right) d\left(|h_{ad}|^2\right) d\left(|h_{dd}|^2\right),$$

$$=\frac{1}{8}\int_0^{\infty} \int_0^{\infty} \int_0^{\infty} e^{-\left(\frac{|h_{sd}|^2\left(1+p_{jd}|h_{ad}|^2\right)}{2\xi^2\left(1+p_{jd}|h_{dd}|^2\right)}\right)} e^{-\frac{|h_{sd}|^2+|h_{ad}|^2+|h_{dd}|^2}{2}} d\left(|h_{sd}|^2\right) d\left(|h_{ad}|^2\right) d\left(|h_{dd}|^2\right), \tag{30b}$$

$$=\frac{1}{4}\int_0^{\infty} \int_0^{\infty} \frac{1+\xi^2 p_{jd}|h_{dd}|^2}{2+p_{jd}\left(|h_{ad}|^2+\xi^2|h_{dd}|^2\right)} e^{-\left(\frac{|h_{ad}|^2+|h_{dd}|^2}{2}\right)} d\left(|h_{ad}|^2\right) d\left(|h_{dd}|^2\right). \tag{30c}$$

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