Outage Performance of Full-duplex Multi-User Relay Systems with Rician Distributed RSI

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***Abstract*—A multi-user full-duplex (FD) two-way relaying system is considered with decode-and-forward relaying protocol. All nodes are assumed to have FD abilities, and residual self-interference (RSI) at each node is modeled as a Rician distributed random variable. Based on the availability of channel state information (CSI) at the relay node, different scheduling schemes are adopted and investigated in terms of outage probability. For the blind case when CSI is unavailable, the random scheduling is analyzed. In the presence of CSI, the absolute channel power based scheduling and normalized channel power based scheduling schemes are considered. A precise closed-form expression for the outage probability is derived for independent and non-identically distributed channels. The theoretical results are verified through Monte-Carlo simulations.**

***Index Terms*—Decode-and-forward, full-duplex, multi-user, outage probability, scheduling.**

I. INTRODUCTION

To improve the spectral efficiency of the multi-user two-way relaying (MUTWR) systems, full-duplex (FD) relays, which can simultaneously transmit and receive, have been adopted as useful technology (see [1]–[5] and references therein). The use of FD relays, however, imposes the residual self-interference (RSI) that exists between transmit and receive antennas of the FD nodes [3]–[5], and limits the system performance. Thus, the characterization of RSI plays an important role in the performance evaluation of FD relaying based communication systems. The experiment-based characterization of FD wireless communication system in [6] proposed that the Rician fading distribution with lower values of its shape parameter[1] K ($K \leq 7$dB before active self-interference (SI) cancellation and $K \leq 3$dB after active SI cancellation) is a better fit for the SI channel than Rayleigh distribution as the Kullback-Leibler (KL) distances obtained from experiments are lower for the Rician distribution.

Most of the available works [5], [7]–[9] related to FD MUTWR systems have considered the constant average RSI power based approach and assumed the RSI as Gaussian or Rayleigh distributed random variables. To the best of authors' knowledge, none of the earlier works evaluated the performance of FD MUTWR systems with Rician distributed RSI. Motivated by these facts and in line with the experimental characterization of RSI, we consider an FD MUTWR system with Rician distributed RSI. Moreover, unlike the constant average RSI power based approach [5], [7]–[9], we consider the effect of instantaneous RSI on the system performance. For the user pair selection, three scheduling schemes namely random (RND) scheduling, absolute (ABS) channel power based scheduling, and normalized (NRM) channel power based scheduling are adopted. The closed-form outage probability expression is obtained for Rayleigh distributed channels.

[1]The shape parameter K is defined as the ratio of the power contributions by line-of-sight (LOS) path to the remaining multi paths.

Notations: The index $\{j\} \in \{1, 2, ..., N\}$, $\{i\} = \{1, 2, ..., N\}$, $\{pq\} \in \{\{Ai\}, \{Bi\}\}$, $\{xy\} \in \{\{aa_i\}, \{bb_i\}, \{rr\}\}$. $Pr\{\cdot\}$ and $\mathbb{E}\{\cdot\}$ denote the probability and the statistical expectation operation, respectively. $|\cdot|$ denotes the absolute value and $\oplus$ is the exclusive-OR operation. Further, $f(\cdot)$ and $\mathcal{F}(\cdot)$ denote the probability density function (PDF) and the cumulative distribution function (CDF), respectively. The additive white Gaussian noise (AWGN) with mean μ and variance σ^2 is represented as $\mathcal{N}(\mu, \sigma^2)$, and $\hat{X}$ denotes the decoded version of signal X.

II. SYSTEM MODEL

The users $A_1, A_2, ..., A_N$ attempt to exchange the information with users $B_1, B_2, ..., B_N$ in pairs with the help of a (two-way) TW FD relay node R. We assume that due to the large separation and strong shadowing effects, the direct link between any user pair A_j and B_j does not exist. The entire relaying operation in one time slot is divided in two phases: multiple access (MAC) phase and broadcast (BC) phase. In the MAC phase, the users A_j and B_j from selected pair j transmit their data to R simultaneously. Then after some signal processing, R broadcasts the received signal in the BC phase.

The channel coefficient between the node A_j and R (R and A_j) is represented as h_{Aj} (g_{Aj}). Similarly, the channel coefficient between the node B_j and R (R and B_j) is represented as h_{Bj} (g_{Bj}). We assume that all the block fading channels h_{pq} and g_{pq} are frequency non-selective and are subject to independent and non-identically distributed (i.ni.d.) Rayleigh fading with parameters $\omega_{pq} = \mathbb{E}\{|h_{pq}|^2\}$ and $\overline{\omega}_{pq} = \mathbb{E}\{|g_{pq}|^2\}$. The squared amplitude of a Rayleigh distributed channel is exponentially distributed with mean $\lambda_{pq} = 1/\omega_{pq}$ $\left(\tau_{pq} = 1/\overline{\omega}_{pq}\right)$ for h_{pq} (g_{pq}). Further, h_{aa_j}, h_{bb_j}, h_{rr} represent the Rician distributed RSI channels at the nodes A_j, B_j, and R, respectively, with scale parameter $\Omega_{xy} + v_{xy}^2 = \mathbb{E}\{|h_{xy}|^2\}$ and shape parameter $K_{xy} = v_{xy}^2/\Omega_{xy}$.

Based on the availability of channel state information (CSI) at R, the RND scheduling, ABS channel power based scheduling, and NRM channel power based scheduling schemes are adopted to select the user pair. The information exchange between the users A_i and B_i of the ith selected pair takes place in following manner: first the users A_i and B_i simultaneously send signals X_{A_i} and X_{B_i}, with transmission powers $P_{A_i} = \mathbb{E}\{|X_{A_i}|^2\}$, $P_{B_i} = \mathbb{E}\{|X_{B_i}|^2\}$, respectively, to R (MAC phase). The received signal at R is written as

$$Y_R = h_{Ai}X_{A_i} + h_{Bi}X_{B_i} + h_{rr}\hat{X}_R + n_R \tag{1}$$

where $n_R \sim \mathcal{N}(0, N_0)$ is the AWGN at R.

After performing bit-level physical-layer network coding [10], the relay R jointly decodes X_{A_i}, X_{B_i} and broadcasts the re-encoded signal $X_R = \hat{X}_{A_i} \oplus \hat{X}_{B_i}$ with transmission power $P_R = \mathbb{E}\{|X_R|^2\}$ to nodes A_i and B_i (BC phase). The signals Y_{A_i} and Y_{B_i} received at nodes A_i and B_i can be written as,

$$\begin{aligned} Y_{A_i} &= g_{Ai}X_R + h_{aa_i}X_{A_i} + n_{A_i}, \\ Y_{B_i} &= g_{Bi}X_R + h_{bb_i}X_{B_i} + n_{B_i} \end{aligned} \tag{2}$$

where $n_{A_i} \sim \mathcal{N}(0, N_0)$ and $n_{B_i} \sim \mathcal{N}(0, N_0)$ represent AWGN at nodes A_i and B_i, respectively.

Using (1) and (2), the respective signal-to-interference-plus-noise-ration (SINRs) for the forward links (A_i-R-B_i) and the backward links (B_i-R-A_i) can be expressed as

$$\begin{aligned} \gamma_{AR} &= \frac{|h_{Ai}|^2 P_{A_i}}{|h_{rr}|^2 P_R + N_0}, \qquad \gamma_{RB} = \frac{|g_{Bi}|^2 P_R}{|h_{bb_i}|^2 P_{B_i} + N_0}, \\ \gamma_{RA} &= \frac{|g_{Ai}|^2 P_R}{|h_{aa_i}|^2 P_{A_i} + N_0}, \qquad \gamma_{BR} = \frac{|h_{Bi}|^2 P_{B_i}}{|h_{rr}|^2 P_R + N_0} \end{aligned} \tag{3}$$

where SINRs at selected nodes A_i and B_i are represented as γ_{RA} and γ_{RB}, respectively; γ_{AR} and γ_{BR} are the SINRs of link from node A_i to R and node B_i to R, respectively. Finally, the sum SINR [2] at R is represented as $\gamma_s = \gamma_{AR} + \gamma_{BR}$.

III. OUTAGE ANALYSIS

The outage is said to be occurred if the selected user pair post scheduling can not exchange the information successfully. In other words, outage is declared when the achievable rate of the ith selected user pair (C_i) is less than the minimum required rate (r_i) [2] i.e., $\mathcal{P}_i \triangleq Pr\{C_i < r_i \mid C_i\}$, where $C_i = \log_2(1 + \gamma_i)$.

For asymmetric traffic requirements, let the forward and the backward links have minimum required rates r_1 and r_2 respectively, and $r = r_1 + r_2$. The respective rate at relay for the MAC channels A_i to R and B_i to R is given by $R_R = \log_2(1 + \gamma_{AR} + \gamma_{BR})$. Then, both data streams can be successfully decoded at relay in the MAC phase if the event $\mathbf{E}_R = \{R_R \geq r\}$ occurs. With both data streams successfully decoded at relay node, the respective rates of BC channels R to A_i and R to B_i are given by $R_{RA} = \log_2(1 + \gamma_{RA})$, $R_{RB} = \log_2(1 + \gamma_{RB})$. Moreover X_{A_i} and X_{B_i} are successfully decoded at nodes B_i and A_i respectively, if the events $\mathbf{E}_{RA} = \{R_{RA} \geq r_2\}$, $\mathbf{E}_{RB} = \{R_{RB} \geq r_1\}$ take place. Let $R_1 = 2^{r_1} - 1$, $R_2 = 2^{r_2} - 1$, and $R = 2^r - 1$. Then the respective probabilities of non-outage events $\mathbf{E}_R$, $\mathbf{E}_{RA}$, and $\mathbf{E}_{RB}$ are given by

$$\begin{aligned} Pr\{\mathbf{E}_R\} &= Pr\{(\gamma_{AR} + \gamma_{BR}) \geq R\}, \\ Pr\{\mathbf{E}_{RA}\} &= Pr\{\gamma_{RA} \geq R_2\}, \\ Pr\{\mathbf{E}_{RB}\} &= Pr\{\gamma_{RB} \geq R_1\}. \end{aligned} \tag{4}$$

Lemma 1. *The outage probability P_{out}^i of the ith scheduled pair is given by*

$$\begin{aligned} P_{out}^i &= 1 - Pr\Big\{\boldsymbol{E}_R \cap \boldsymbol{E}_{RA} \cap \boldsymbol{E}_{RB}\Big\} \\ &= 1 - \Big(Pr\{\boldsymbol{E}_R\}\, Pr\{\boldsymbol{E}_{RA}\}\, Pr\{\boldsymbol{E}_{RB}\}\Big) \end{aligned} \tag{5}$$

where $Pr\{\boldsymbol{E}_R\}$, $Pr\{\boldsymbol{E}_{RA}\}$, and $Pr\{\boldsymbol{E}_{RB}\}$ are defined in (11)*,* (12)*, and* (13)*, respectively.*

Proof: See appendix A ■

Now, we analyze the performance of different multi-user scheduling schemes.

1) RND Scheduling: As all user pairs are equally probable, the outage probability of system with the RND scheduling can be written as

$$P_{out}^{RND} = \frac{1}{N}\sum_{i=1}^{N} P_{out}^i \tag{6}$$

where P_{out}^i is given by (5).

2) ABS Channel Power Based Scheduling: The authors in [11] considered the availability of CSI at R, and used the instantaneous SINR to schedule the ith user pair. However in FD MUTWR system, the ABS-SINR based scheduling presented in [11] can't be directly applied. This is due to the fact that the relay requires the future CSI of user node channels g_{Ai}, h_{aai}, g_{Bi}, and h_{bbi}. Thus for scheduling purpose, in this paper, the ABS channel power based scheduling is used in which the user pair i with the maximum instantaneous channel power of MAC link is chosen i.e., $i = \arg\ \max_{i\in j}\left\{min(|h_{Ai}|^2, |h_{Bi}|^2)\right\}$. The system outage probability for ABS channel power based scheduling is given as [11]

$$P_{out}^{ABS} = \prod_{i=1}^{N} P_{out}^i. \tag{7}$$

3) NRM Channel Power Based Scheduling: Although the selection of user pair based on maximum instantaneous channel power enhances the system throughput, it can lead to a biased scheduling of the system resources among all the users. Hence, a modified selection criterion of users based on the relative channel power is considered in NRM channel power based scheduling. The user pair i is chosen as $i = \arg\ \max_{i\in j}\left\{\frac{\min(|h_{Ai}|^2, |h_{Bi}|^2)}{\overline{\Gamma}_i}\right\}$ where $\overline{\Gamma}_i$ is the average value of $\min(|h_{Ai}|^2, |h_{Bi}|^2)$ for the ith user pair. Based on this criterion, system outage probability for NRM channel power based Scheduling is given as [11]

$$P_{out}^{NRM} = \frac{1}{N}\sum_{i=1}^{N}\left(\overline{P}_{out}^{\,i}\right)^N. \tag{8}$$

The expression for the $\overline{P}_{out}^{i}$ can be similarly derived and is obtained by replacing $\overline{\gamma}_{\widetilde{ar}}$, $\overline{\gamma}_{\widetilde{rb}}$, $\overline{\gamma}_{\widetilde{ra}}$, and $\overline{\gamma}_{\widetilde{br}}$ with $\overline{\Gamma}_i$ in the expression P_{out}^{i} given by (5).

IV. Numerical Results and Discussions

The parameters ω_{pq} and $\overline{\omega}_{pq}$ are generated between 0.5 and 1 randomly. Minimum required rates $r_1 = r_2 = 1$ bps/Hz, $N_0 = 1$ and number of user pairs $N = 8$. Monte Carlo (MC) simulations for the outage probability are presented to verify the theoretical analysis and are performed over 10^8 samples.

In Fig. 1, we investigate the outage probability of absolute SINR based scheduling with transmit relay power P_r. We set the transmit powers $P_{B_i} = P_{A_i} = 20$ dBW, the RSI parameters $\Omega_{xy} = -15$ dBW and K-factor values K_{xy} are varied as shown in Fig. 1. We note that power contributions by LOS component of RSI at relay node (K_{rr}) have greater impact on the outage performance in the high transmit power regime while K_{aai}, K_{bbi} severely affect the outage performance in the low transmit power regime. It can be seen that the outage probability of system first decreases with P_r and is better for smaller values of Rician parameter K_{xy}. However, when P_r exceeds 20 dBW, the outage probability of system again increases with P_r as the high transmit power strengthens the RSI which further decreases the SINR. MC simulations for the exact outage probability show the close resemblance to the derived theoretical outage probability.

In Fig. 2a, we explore the impact of $\Omega_{aa_i} = \Omega_{bb_i} = \Omega$ on the outage probability of system for RND scheduling. The parameters Ω_{rr} is set equal to -15 dBW and $P_R = P_{pq} = 30$ dBW. The results infer that the outage probabilities decrease monotonically for the negative values of Ω and then becomes small and almost constant. This concludes that for practical implementation of FD system, it is sufficient to minimize the self-interference below certain threshold value. Further, it is also noted that beyond -35 dBW, the outage curves for different values of K_{aa_i} and K_{bb_i} with fixed K_{rr} converge to a constant value and the performance of system can not be improved further. In contrast, the curves for different values of K_{rr} with fixed K_{aa_i} and K_{bb_i} saturate to different values of outage probability i.e. higher outage probability for higher K_{rr}. This infers that, for given RSI at relay and user nodes, the RSI of relay node will affect the system more severely and higher K_{rr} results in poorer performance, which theoretically validates the experimental observation.

Fig. 2b and Fig. 2c investigate the outage probability of the system for ABS SINR-based scheduling with the ratio of transmit powers of relay node to user nodes assuming $P_{pq} = P_S$. From Fig. 2b and Fig. 2c we conclude that for a fixed user nodes transmit power P_S, there exists an optimum power level to be transmitted from relay (P_R) which results in minimum outage probability. For example, in Fig. 2c, for $P_S = 5$ dBW, the minimum system outage probability is obtained at $P_R \approx 13$ dBW which implies $P_R/P_S \approx 2.6$. The same can be verified in Fig. 2b, where for different values of P_S, the minima of outage probability is obtained at different P_R (dBW)/P_S (dBW) ratios. Moreover, unlike [5, Fig. 3]

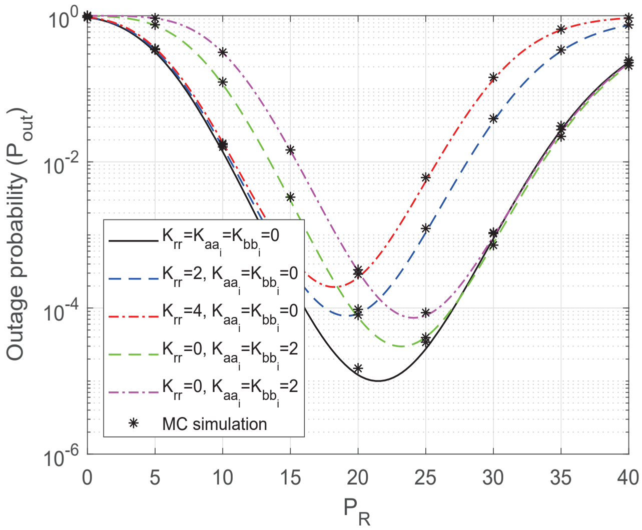


Fig. 1: Outage probability of absolute SINR scheduling versus transmit power of relay node P_R with $P_{A_i} = P_{B_i} = 20$ dBW.

where it is concluded that beyond $P_R = P_S$ any increase in P_R deteriorates the performance, it can be concluded from Fig. 2b that the value of P_R after which performance degradation starts, depends on transmitted power P_S and the minimum outage probability can be achieved by proper selection of P_R for a given P_S.

V. Conclusions

The outage performance of an FD MUTWR system for different scheduling schemes was studied with Rician distributed RSI. Further, it was also concluded that for given RSI at relay and user nodes, the RSI at relay will degrade system performance more severely. Moreover, the minimum system outage probability can be achieved by proper selection of P_R and P_S and a slight deviation from optimal value of P_R results in severely degraded performance.

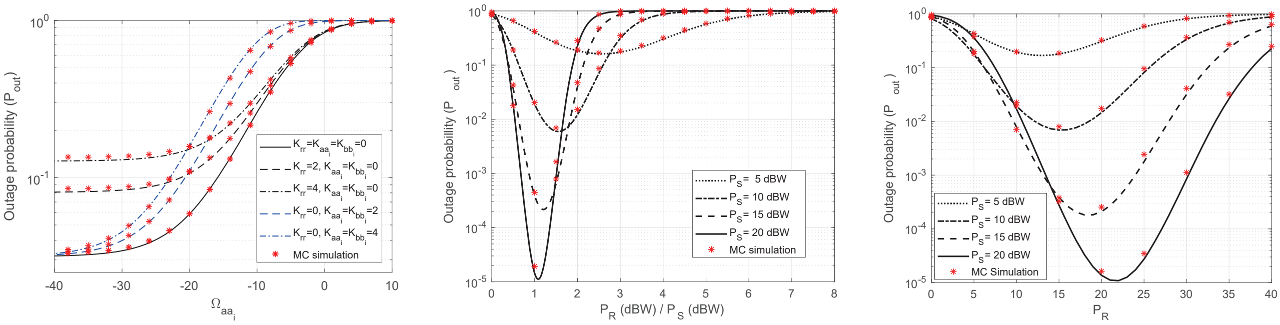
Appendix A
Proof of Lemma 1

In (3), let $c_1 = P_{A_i}/P_R$, $c_1' = P_{B_i}/P_R$, $c_2 = N_0/P_R$, $c_3 = P_R/P_{A_i}$, $c_3' = P_R/P_{B_i}$, $c_4 = N_0/P_{A_i}$, and $c_4' = N_0/P_{B_i}$. The PDF of $|h_{pq}|^2$ and $|g_{pq}|^2$ follows exponential distribution given by

$$f_{|h_{pq}|^2}(t) = \frac{2t}{\omega_{pq}} e^{\left(\frac{-t^2}{\omega_{pq}}\right)}, \quad f_{|g_{pq}|^2}(u) = \frac{2u}{\overline{\omega}_{pq}} e^{\left(\frac{-u^2}{\overline{\omega}_{pq}}\right)} \tag{9}$$

for $t, u \geq 0$. The PDF of $|h_{xy}|^2$ is given by

$$f_{|h_{xy}|^2}(t) = \frac{1}{\Omega_{xy}} e^{\left(\frac{-\left(t+v_{xy}^2\right)}{\Omega_{xy}}\right)} \mathcal{I}_0\left(\frac{2v_{xy}\sqrt{t}}{\Omega_{xy}}\right) \tag{10}$$



(a) Impact of K-factor (b) Optimum value of ratio P_R/P_S (c) Impact of transmit power P_S

Fig. 2: Outage probability of the system under impact of RSI.

for $t \geq 0$ where $\mathcal{I}_0(\cdot)$ is the modified Bessel function of the first kind [12]. Then $Pr\{\mathbf{E}_R\}$ in (5) is calculated as

$$\begin{aligned} Pr\{\mathbf{E}_R\} &= 1 - Pr\{(\gamma_{AR} + \gamma_{BR}) \leq R\} \\ &= 1 - \mathbb{E}_{|h_{rr}|^2}\left[\int_0^{R(|h_{rr}|^2+c_2)} f_{c_1|h_{Ai}|^2 + c_1'|h_{Bi}|^2}(t)\,\mathrm{d}t\right] \\ &= 1 - \mathbb{E}_{|h_{rr}|^2}\left[\int_0^{R(|h_{rr}|^2+c_2)} \frac{\lambda_{Ai}\lambda_{Bi}(e^{\frac{\lambda_{Ai}t}{c_1}} - e^{\frac{\lambda_{Bi}t}{c_1'}})}{c_1\lambda_{Bi} - c_1'\lambda_{Ai}}\,\mathrm{d}t\right] \\ &= 1 - \int_0^{\infty}\left\{\frac{\Psi P_{Ai}}{\lambda_{Ai}}\left(1 - e^{-\left(\frac{\lambda_{Ai}R(|h_{rr}|^2+c_2)}{c_1}\right)}\right) - \right. \\ &\quad \left.\frac{\Psi P_{Bi}}{\lambda_{Bi}}\left(1 - e^{-\left(\frac{\lambda_{Bi}R(|h_{rr}|^2+c_2)}{c_1'}\right)}\right)\right\} f_{|h_{rr}|^2}(z)\,\mathrm{d}z \end{aligned}$$

or

$$\begin{aligned} Pr\{\mathbf{E}_R\} &= \frac{\Psi P_{A_i}}{\lambda_{Ai}}\left(\frac{e^{-\left(\lambda_{rr}v_{rr}^2 + \frac{c_2\lambda_{rr}}{(1+c_2\lambda_{rr})\overline{\gamma}_{ar}}\right)} e^{\left(\frac{\lambda_{rr}v_{rr}^2}{1+\frac{1}{(1+c_2\lambda_{rr})\overline{\gamma}_{ar}}}\right)}}{1 + \frac{1}{(1+c_2\lambda_{rr})\overline{\gamma}_{ar}}}\right) - \\ &\quad \frac{\Psi P_{B_i}}{\lambda_{Bi}}\left(\frac{e^{-\left(\lambda_{rr}v_{rr}^2 + \frac{c_2\lambda_{rr}}{(1+c_2\lambda_{rr})\overline{\gamma}_{br}}\right)} e^{\left(\frac{\lambda_{rr}v_{rr}^2}{1+\frac{1}{(1+c_2\lambda_{rr})\overline{\gamma}_{br}}}\right)}}{1 + \frac{1}{(1+c_2\lambda_{rr})\overline{\gamma}_{br}}}\right) \end{aligned} \tag{11}$$

where $\Psi = \lambda_{Ai}\lambda_{Bi}/(P_{Bi}\lambda_{Bi} - P_{Ai}\lambda_{Ai})$. The term $\overline{\gamma}_{uv}$ is the average SINR of the uv link and is defined as $\overline{\gamma}_{uv} = \mathbb{E}\{\gamma_{uv}\}$ with $\{uv\} \in \{\{ar\}, \{br\}, \{ra\}, \{rb\}\}$. The terms $\overline{\gamma}_{ar}$ and $\overline{\gamma}_{br}$ in (11) are given by $\overline{\gamma}_{ar} = \mathbb{E}\left\{\frac{c_1|h_{Ai}|^2}{R_1(|h_{rr}|^2+c_2)}\right\} = \frac{c_1\lambda_{rr}}{R_1\lambda_{Ai}(1+c_2\lambda_{rr})}$, and $\overline{\gamma}_{br} = (c_1'\lambda_{rr})/(R_2\lambda_{Bi}(1+c_2\lambda_{rr}))$.

In a similar way,

$$Pr\{\mathbf{E}_{RA}\} = 1 - \mathbb{E}_{|h_{aai}|^2}\left[Pr\left\{|g_{Ai}|^2 \leq \frac{R_2(|h_{aai}|^2 + c_4)}{c_3}\right\}\right]$$

$$Pr\{\mathbf{E}_{RA}\} = \frac{e^{-(\lambda_{aai}v_{aai}^2)} e^{\left(\frac{-c_4\lambda_{aai}}{(1+c_4\lambda_{aai})\overline{\gamma}_{ra}}\right)} e^{\left(\frac{\lambda_{aai}v_{aai}^2}{1+\frac{1}{(1+c_4\lambda_{aai})\overline{\gamma}_{ra}}}\right)}}{1 + \frac{1}{(1+c_4\lambda_{aai})\overline{\gamma}_{ra}}} \tag{12}$$

where $\overline{\gamma}_{ra} = (c_3\lambda_{aai})/(R_2\tau_{Ai}(1 + c_4\lambda_{aai}))$. Similarly,

$$Pr\{\mathbf{E}_{RB}\} = \frac{e^{-(\lambda_{bbi}v_{bbi}^2)} e^{\left(\frac{-c_4'\lambda_{bbi}}{(1+c_4'\lambda_{bbi})\overline{\gamma}_{rb}}\right)} e^{\left(\frac{\lambda_{bbi}v_{bbi}^2}{1+\frac{1}{(1+c_4'\lambda_{bbi})\overline{\gamma}_{rb}}}\right)}}{1 + \frac{1}{(1+c_4'\lambda_{bbi})\overline{\gamma}_{rb}}}, \tag{13}$$

where $\overline{\gamma}_{rb} = (c_3'\lambda_{bbi})/(R_1\tau_{Bi}(1 + c_4'\lambda_{bbi}))$.

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