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Relay selection in two-way relaying network with the presence of hardware impairment at relay transceiver

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Abstract—In this paper, we analyze the performance of two-way amplify-and-forward (AF) relaying with best relay selection scheme in the presence of hardware impairment at the relays. We first obtain the tractable closed-form expressions of the statistical characteristics for end-to-end signal-to-noise ratio (SNR). To reveal significant insights into the system performance, we also computed the asymptotic SEP, which is shown extremely tight in the high SNR regime and low hardware impairments level. Our analysis enables us to evaluate the impact of non-ideal hardware on the performance of two-way relaying networks and highlight as a benchmark for system designer.

Index Terms—relay hardware impairment, relay selection, amplify-and-forward

I. INTRODUCTION

A two-way AF relaying network has two sources and a single or multiple relays. In the first time slot, two source nodes transmit signal to the relay (for single relay network) or to all relays (for multiple relays network) simultaneously. In single relay network, the relay received the superimposed signal from two source node. In the second time slot, the relay amplifies the received signal and then forward it to two source nodes. The performance of single relay network using AF protocol was discussed in [1], [2].

Many researchs showed that the performance of a wireless network with multiple relays is improved by using relay selection methods. In [3], it presented a Max - Min sum rate selection method based on outage probability. [4] has a algorithm of selecting the relay so that the received SNR is maximized. In [5], the author proposed a Max-Min SNR selection method. In [6], the diversity orders of many the single-relay selection schemes in a two-way wireless relay network is analyzed. A Min-Max criterion for relay selection is introduced in [7], where a relay with a minimizes the maximum SEP of two sources will be selected. The selection scheme in [7] also showed that it has full diversity order of N if the system has N relays but it provide better BER than all-participate amplify-and-forward (AP-AF) relaying scheme.

The analyses in above researchs are done with the assumption that the hardware of the relays are perfect. In practice, the hardware is affected by impairments such as IQ imbalance,

amplifier non-linearities, and phase noise (see [8]), and the hardware impairments of the relays always have many effects on wireless communications.

To make the system more realistic, in this paper, we will analyze a relay selection of two-way AF relaying network as proposed in [7] but with the presence of hardware impairment at relaying nodes. Our purpose is the consider of the effects of hardware impairments on relay selection of two-way AF relaying wireless network.

The paper is organized as follows. The system model for considered two-way multiple relays AF network is described in Section II. In that section we extract the expressions of transmission/received signals at two source nodes and at the relays of network. Then, in section III, we introduce two relay selection amplify-and-forward (RS-AF) scheme: Optimal Relay Selection Amplify-and-Forward (O-RS-AF) and Sub-optimal Relay Selection Amplify-and-Forward (S-RS-AF). Our analysis concentrate on the proposed Min-Max selection criterion of S-RS-AF method and the asymptotic SEP is also computed. Numerical results are shown in section IV and finally, section V is our conclusion.

Notation: $\mathcal{CN}(\mu, \sigma^2)$ is complex Gaussian distribution with mean μ and variance σ^2 . $Var\{\cdot\}$, $E\{\cdot\}$ are variance and expectation of random variable. $K_n(\cdot)$ is the n th-order modified Bessel function of the second kind .

II. SYSTEM AND CHANNEL MODEL

Consider two-way relaying network with two source nodes denoted by S_1 and S_2 and N relays denoted by R_1, R_2, \dots, R_N . All nodes have single antenna. In the first time slot, both source nodes send information to all relays. Each relay receive the super-position signal from S_1 and S_2 . In the second time slot, an optimal relay node is selected to forward received signal to two source nodes while other relays keep idle. In this model, we use quasi-static Rayleigh fading channels with additive white Gaussian noise. We assume that all sources or relay nodes know can have perfect channel estimation. The method of selection the relay node as in [7], but this paper research the condition when each relay node suffer the impairment of transceiver hardware.

The symbol transmitted by S_i is s_i ($i = 1, 2$). The signal received at the k -th relay in first time slot is:

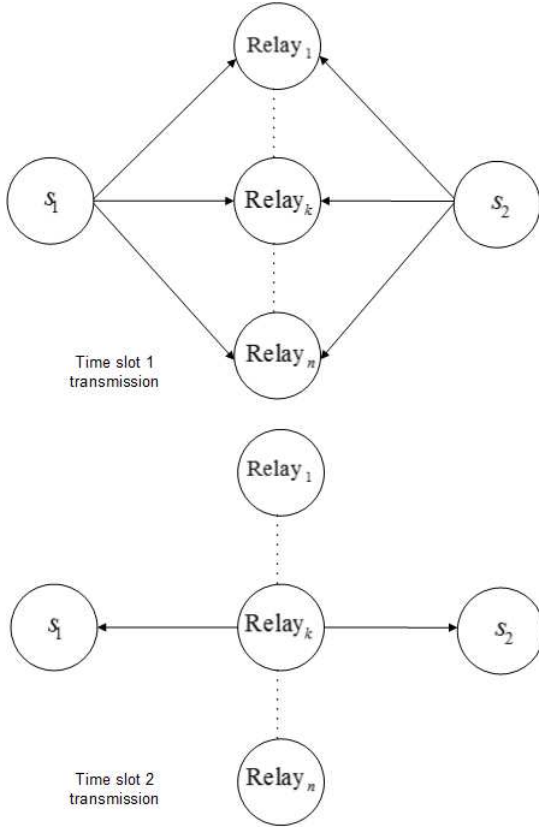


Fig. 1. Relay selection network

$$y_{r_k} = \sqrt{p_s} h_{1,r_k} s_1 + \sqrt{p_s} h_{2,r_k} s_2 + n_{r_k} + \eta_{r_k} \quad (1)$$

where p_s is transmit power at source nodes S_1 and S_2 , h_{i,r_k} ($i = 1, 2; k = 1, 2, \dots, N$) are fading coefficient between S_i and R_k with zero mean and unit variance; n_{r_k} is additive white noise $n_{r_k} \sim \mathcal{CN}(0, N_0)$; η_{r_k} is hardware distortion noise of relay receiver of R_k : $\eta_{r_k} \sim \mathcal{CN}(0, \kappa_r^2(p_s(|h_{1,r_k}|^2 + p_s|h_{2,r_k}|^2))$ (see A for hardware impairment model).

The relay R_k then processes the received signal and forward to two source nodes. The signal generate by the relay is:

$$x_{r_k} = \beta_k y_{r_k} \quad (2)$$

where β_k is amplification factor. It can be expressed as $\beta_k = ((p_s|h_{1,r_k}|^2 + p_s|h_{2,r_k}|^2)(1 + \kappa_r^2) + N_0)^{-1/2}$.

Denote η_{t_k} is hardware impairment of transmitter at the relay: $\eta_{t_k} \sim \mathcal{CN}(0, \kappa_t^2 p_r)$, p_r is transmit power of the relay.

The relay forward x_{r_k} to two source nodes S_i ($i = 1, 2$), if y'_{i,r_k} is the signal received at S_i from R_k , it can be written as

$$y'_{i,r_k} = \sqrt{p_r} h_{i,r_k} x_{r_k} + h_{i,r_k} \eta_{t_k} + n_{i,r_k}, \quad i = 1, 2 \quad (3)$$

Denote $\alpha_k = \sqrt{p_s p_r} \beta_k h_{1,r_k} h_{2,r_k}$, $\omega_{1,r_k} = \sqrt{p_r} \beta_k h_{1,r_k} (n_{r_k} + \eta_{r_k}) + h_{1,r_k} \eta_{t_k} + n_{1,r_k}$, $\omega_{2,r_k} = \sqrt{p_r} \beta_k h_{2,r_k} (n_{r_k} + \eta_{r_k}) + h_{2,r_k} \eta_{t_k} + n_{2,r_k}$. Combine (1), (2), (3) and after subtracting its own information, each source node S_i ($i = 1, 2$) we have the received signal of each source node

$$y_{1,r_k} = \alpha_k s_2 + \omega_{1,r_k}, \quad y_{2,r_k} = \alpha_k s_1 + \omega_{2,r_k}$$

The recover signal can be archived by using Maximum likelihood detector. Two relay selection schemes are discussed in the next section.

III. SEP ANALYSIS

We use relay selection methods to choose one best relay and then transmit the super-position signal to two sources. We have two relaying selection methods, as proposed in [7]:

1). Optimal Relay Selection Amplify-and-Forward (O-RS-AF) scheme: The selected relay denoted by \mathcal{R} which has the minimum SEP from both source:

$$\mathcal{R} = \min_k \{ SEP_{1,r_k}(\gamma_{1,r_k} | h_{1,r_k}, h_{2,r_k}), + SEP_{2,r_k}(\gamma_{2,r_k} | h_{1,r_k}, h_{2,r_k}) \} \quad (4)$$

$SEP_{1,r_k}(\gamma_{1,r_k} | h_{1,r_k}, h_{2,r_k})$, $i = 1, 2$ are SEP at source nodes S_i from k -th relay with channel coefficient h_{1,r_k}, h_{2,r_k} . According to [7] we have $SEP_{i,r_k}(\gamma_{i,r_k} | h_{1,r_k}, h_{2,r_k}) = Q(\sqrt{c\gamma_{i,r_k}})$, which $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp(-t^2/2) dt$ is Q is $Q(\cdot)$ function and if we use BPSK modulation we have $c = 2$. γ_{i,r_k} is SNR at source nodes:

$$\gamma_{i,r_k} = \frac{|\alpha_k|^2}{Var\{\omega_{i,r_k}\}}$$

2). Sub-Optimal Relay Selection Amplify-and-Forward (S-RS-AF) scheme: It is very difficult to analyze (4), so a new Min-Max selection criteria is proposed. The Min-Max selection can be describes by following equation

$$\mathcal{R} = \min_k \max \{ SEP_{1,r_k}(\gamma_{1,r_k} | h_{1,r_k}, h_{2,r_k}), SEP_{2,r_k}(\gamma_{2,r_k} | h_{1,r_k}, h_{2,r_k}) \} \quad (5)$$

Equation (5) is equivalent to estimate the SNR equation

$$\gamma_R = \max_k \min \{ \gamma_{1,r_k}, \gamma_{2,r_k} \}, \quad k = 1, \dots, N \quad (6)$$

Theorem 1. Define $\psi_r \triangleq \frac{p_r}{N_0(1+\kappa_r^2)}$, $\psi_s \triangleq \frac{p_s}{N_0(1+\lambda)(1+\kappa_s^2)}$ with $\lambda \triangleq \frac{p_s(1+\kappa_r^2)}{p_r(1+\kappa_s^2)}$. In high SNR regime and low impairments level, the asymptotic average SEP of this S-RS-AF scheme is:

$$SEP_{RS} = \frac{(2N-1)!!}{2} \left(\frac{\psi}{c}\right)^N \quad (7)$$

where $(2n-1)!! \triangleq \prod_{k=1}^n (2k-1) = \frac{(2n-1)!}{n!2^n}$ and $\psi = 2(\psi_r^{-1} + \psi_s^{-1})$.

Proof: First, we compute the PDF and CDF of γ_R from equation (6).

γ_{1,r_k} and γ_{2,r_k} has the same PDF and CDF, denoted by $f_{\gamma_k}(x)$ and $F_{\gamma_k}(x)$.

$$\gamma_{1,r_k} = \frac{|\alpha_k|^2}{Var\{\omega_{1,r_k}\}} \quad (8)$$

$$\begin{aligned} \text{Var}\{\omega_{1,r_k}\} &= p_r \beta_k^2 N_0 |h_{1,r_k}|^2 \\ &+ p_r \beta_k^2 |h_{1,r_k}|^2 \kappa_r^2 (p_s |h_{1,r_k}|^2 + p_s |h_{2,r_k}|^2) \\ &+ |h_{1,r_k}|^2 \kappa_t^2 p_r + N_0 \end{aligned} \quad (9)$$

After some computational steps, we have:

$$\gamma_{1,r_k} = \frac{\frac{p_s}{N_0} \frac{p_r}{N_0} |h_{1,r_k}|^2 |h_{2,r_k}|^2}{\left(\frac{p_r(1+\kappa_t^2)+p_s(1+\kappa_r^2)}{N_0} \right) |h_{1,r_k}|^2 + \frac{p_s(1+\kappa_r^2)}{N_0} |h_{2,r_k}|^2 + \xi}$$

where

$$\begin{aligned} \xi &= 1 + \frac{|h_{1,r_k}|^2 |h_{2,r_k}|^2 (p_r p_s \kappa_r^2 + p_s p_r (1 + \kappa_r^2) \kappa_t^2)}{N_0^2} \\ &+ \frac{|h_{1,r_k}|^4 (p_r p_s \kappa_r^2 + p_s p_r (1 + \kappa_r^2) \kappa_t^2)}{N_0^2} \end{aligned} \quad (11)$$

Define $\psi_r \triangleq \frac{p_r}{N_0(1+\kappa_r^2)}$, $\psi_s \triangleq \frac{p_s}{N_0(1+\lambda)(1+\kappa_t^2)}$ with $\lambda \triangleq \frac{p_s(1+\kappa_r^2)}{p_r(1+\kappa_t^2)}$ we can rewrite (10) as:

$$\begin{aligned} \gamma_{1,r_k} &= \frac{\psi_r \psi_s |h_{1,r_k}|^2 |h_{2,r_k}|^2}{\psi_r |h_{1,r_k}|^2 + \psi_s |h_{2,r_k}|^2 + \xi'} \\ &\approx \frac{\psi_r \psi_s |h_{1,r_k}|^2 |h_{2,r_k}|^2}{\psi_r |h_{1,r_k}|^2 + \psi_s |h_{2,r_k}|^2} \end{aligned} \quad (12)$$

where $\xi' \rightarrow 0$ when SNR is high and $\kappa_r, \kappa_t \rightarrow 0$.

(The remain proof of this theorem can refer to [7]).

Define $\gamma_k^{min} \triangleq \min\{\gamma_{1,r_k}, \gamma_{2,r_k}\}$, $f_{\gamma_k^{min}}(x)$ and $F_{\gamma_k^{min}}(x)$ are PDF and CDF function, respectively. Using order statistics as in [9], we can calculate PDF of γ_R :

$$f_{\gamma_R}(x) = N f_{\gamma_k^{min}}(x) F_{\gamma_k^{min}}^{N-1}(x) \quad (13)$$

$$F_{\gamma_R}(x) = F_{\gamma_k^{min}}^N(x) \quad (14)$$

where $f_{\gamma_k^{min}}(x) = 2f_{\gamma_k}(x)(1-F_{\gamma_k}(x))$, $F_{\gamma_k^{min}}(x) = 1 - (1-F_{\gamma_k}(x))^2$

From equations (13) and (14):

$$f_{\gamma_R}(x) = 2N f_{\gamma_k}(x) (1-F_{\gamma_k}(x)) [1-(1-F_{\gamma_k}(x))^2]^{N-1} \quad (15)$$

From (12), let $X_1 \triangleq \psi_s |h_{1,r_k}|^2$, $X_2 \triangleq \psi_r |h_{2,r_k}|^2$:

$$\gamma_{1,r_k} = \frac{1}{\frac{1}{\psi_s |h_{1,r_k}|^2} + \frac{1}{\psi_r |h_{2,r_k}|^2}} = \frac{1}{2} \frac{2}{\frac{1}{X_1} + \frac{1}{X_2}}$$

$\frac{2}{\frac{1}{X_1} + \frac{1}{X_2}}$ is harmonic mean of two random variables has exponential distributed function:

$$p_{X_i}(x) = \beta_i e^{-\beta_i x} U(x)$$

where $\beta_1 = 1/\psi_s$, $\beta_2 = 1/\psi_r$. $U(x)$ is unit step function.

According [10] $X = \mu_H(X_1, X_2) = \frac{2}{\frac{1}{X_1} + \frac{1}{X_2}}$ has PDF:

$$\begin{aligned} f_X(x) &= \frac{1}{2} \beta_1 \beta_2 x e^{-\frac{x(\beta_1+\beta_2)}{2}} \left[\left(\frac{\beta_1 + \beta_2}{\sqrt{\beta_1 \beta_2}} \right) \times K_1(x \sqrt{\beta_1 \beta_2}) \right. \\ &\quad \left. + 2K_0(x \sqrt{\beta_1 \beta_2}) \right] U(x) \end{aligned} \quad (16)$$

$K_0(\cdot), K_1(\cdot)$ are zeroth-order and first-order modified Bessel functions of the second kind.

Let $X' = \frac{1}{2} \mu_H(X_1, X_2) = \frac{1}{2} X$. Substituted $x = 2x'$ in (16), we have PDF of X' (notice that $dx = 2dx'$):

$$\begin{aligned} f_{\gamma_k}(x) &= 2\beta_1 \beta_2 x e^{-x(\beta_1+\beta_2)} \times \left[\left(\frac{\beta_1 + \beta_2}{\sqrt{\beta_1 \beta_2}} \right) \times K_1(2x \sqrt{\beta_1 \beta_2}) \right. \\ &\quad \left. + 2K_0(2x \sqrt{\beta_1 \beta_2}) \right] U(x) \end{aligned}$$

Because $\beta_1 + \beta_2 = \psi_r^{-1} + \psi_s^{-1}$, $\beta_1 \beta_2 = \frac{1}{\psi_r \psi_s}$, $\frac{\beta_1 + \beta_2}{\sqrt{\beta_1 \beta_2}} = \frac{\psi_r + \psi_s}{\sqrt{\psi_r \psi_s}}$, so:

$$\begin{aligned} f_{\gamma_k}(x) &= \frac{2x e^{-x(\psi_r^{-1} + \psi_s^{-1})}}{\psi_r \psi_s} \times \left[\frac{\psi_r + \psi_s}{\sqrt{\psi_r \psi_s}} \times K_1\left(\frac{2x}{\sqrt{\psi_r \psi_s}}\right) \right. \\ &\quad \left. + 2K_0\left(\frac{2x}{\sqrt{\psi_r \psi_s}}\right) \right] U(x) \end{aligned}$$

And we also have $K_1(z) \rightarrow 1/z$ when $z \rightarrow 0$, $K_0(z) \rightarrow 0$ when $z \rightarrow 0$. So when SNR is high:

$$f_{\gamma_k} = \frac{2x}{\psi_r \psi_s} e^{-x(\psi_r^{-1} + \psi_s^{-1})} \times \frac{\psi_r + \psi_s}{\sqrt{\psi_r \psi_s}} \times \frac{\sqrt{\psi_r \psi_s}}{2x}$$

$$\begin{aligned} f_{\gamma_k} &= \frac{\psi_r + \psi_s}{\psi_r \psi_s} e^{-x(\psi_r^{-1} + \psi_s^{-1})} \\ &= (\psi_r^{-1} + \psi_s^{-1}) e^{-x(\psi_r^{-1} + \psi_s^{-1})} = \frac{\psi}{2} e^{-\frac{\psi}{2} x} \end{aligned} \quad (17)$$

where $\psi = 2(\psi_r^{-1} + \psi_s^{-1})$.

And the CDF is:

$$F_{\gamma_k}(x) = 1 - e^{-\frac{\psi}{2} x} \quad (18)$$

Replace $f_{\gamma_k}(x), F_{\gamma_k}(x)$ from (17),(18) to (15), we have:

$$f_{\gamma_R}(x) = N \psi e^{-\psi x} (1 - e^{-\psi x})^{N-1}$$

The fact that $(1 - e^{-x}) \approx x$ when $x \rightarrow 0$ (Taylor series), so when SNR goes high ($\psi \rightarrow 0$), from (14) and (18):

$$F_{\gamma_R}(x) = F_{\gamma_k^{min}}^N(x) = [1 - (1 - F_{\gamma_k}(x))^2]^N = (1 - e^{-\psi x})^N \rightarrow (\psi x)^N \quad (19)$$

The average SEP can be computed with equation:

$$SEP_{RS} = \mathbb{E}[SEP(\gamma_R | h_1, h_2)] = \mathbb{E}[Q(\sqrt{c\gamma_R})]$$

c is a constant determined by the modulation format, if use BPSK modulation then $c = 2$.

If X is a random variables with $X \sim \mathcal{N}(0, 1)$, the average SEP can be rewritten as:

$$\begin{aligned}
SEP &= P\{X > \sqrt{c\gamma_R}\} = P\{\gamma_R < \frac{X^2}{c}\} \\
&= \mathbb{E}[F_{\gamma_R}(\frac{X^2}{c})] = \int_0^\infty F_{\gamma_R}(\frac{X^2}{c})F_X(x)dx
\end{aligned}$$

From (19) and $X \sim \mathcal{N}(0, 1)$ we have:

$$SEP_{RS} = \frac{1}{\sqrt{2\pi}} \left(\frac{\psi}{c}\right)^N \int_0^\infty x^{2N} e^{-\frac{x^2}{2}} dx$$

Using the result from [11]: $\int_0^\infty t^{2n} e^{-kt^2} dt = \frac{(2n-1)!!}{2(2k)^n} \sqrt{\frac{\pi}{k}}$ with $(2n-1)!! \triangleq \prod_{k=1}^n (2k-1) = \frac{(2n-1)!}{n!2^n}$, replace $k = 1/2$ we have:

$$SEP_{RS} = \frac{(2N-1)!!}{2} \left(\frac{\psi}{c}\right)^N \quad (20)$$

Noticed that $\psi = 2(\psi_r^{-1} + \psi_s^{-1}) < 1$ so from SEP at (20) we see that the diversity of this S-RS-AF scheme is N when using N relay nodes.

We have following corollary:

Corollary 2. a) If the relay transceiver is ideal, or $\kappa_r = \kappa_t = 0 \Rightarrow \psi_r = \frac{p_r}{N_0}, \psi_s = \frac{p_s}{N_0(1+\lambda)}, \lambda = \frac{p_s}{p_r}$, we have the same result of ψ_r, ψ_t, λ and the equation (12) as in [7].

b) Denote $SNR = p_s/N_0$ is signal-noise ratio of source, we have $N_0/p_s = 1/SNR, N_0/p_r = \lambda(1+\kappa_t^2)/(1+\kappa_r^2) * 1/SNR$ and $\psi = 2(\psi_r^{-1} + \psi_s^{-1}) = 2\frac{1}{SNR}(1+2\lambda)(1+\kappa_t^2)$, (20) become:

$$SEP_{RS} = \frac{(2N-1)!!}{2} \left(\frac{\psi}{c}\right)^N = \frac{(2N-1)!}{N!2c^N} \frac{(1+2\lambda)^N}{SNR^N} (1+\kappa_t^2) \quad (21)$$

IV. NUMERICAL RESULTS AND DISCUSSION

In this simulation, we assume both source nodes have the SNR. BPSK modulation is used and all channels are symmetric Rayleigh fading channels.

Total energy of two source nodes S_1, S_2 and all relays $R_k (k = 1, \dots, N)$ are p . The number $N = 1, 2, 3, 4$ relay nodes is used in these simulations.

Noise variance off all channels are N_0 .

With Relay Selection Scheme in this paper, we only has a single relay work to forward signal to two source nodes. In this simulation, $p_s = p_r = 1$.

As in [6], the system is outage if the hardware impairment coefficient is over 0.2, so all the simulation we use the low hardware impairment levels to satisfy the assumption of this research.

Figure 2 is the result average SEP of O-RS-AF and S-RS-AF with the hardware impairment level is $\kappa_r = 0.01, \kappa_t = 0.03$, we can see that the O-RS-AF method and S-RS-AF has the same performance result. With different levels of impairments we always has the same result of O-RS-AF and S-RS-AF but because the limit length of this paper we don't include them in. From that figure we see that the performance

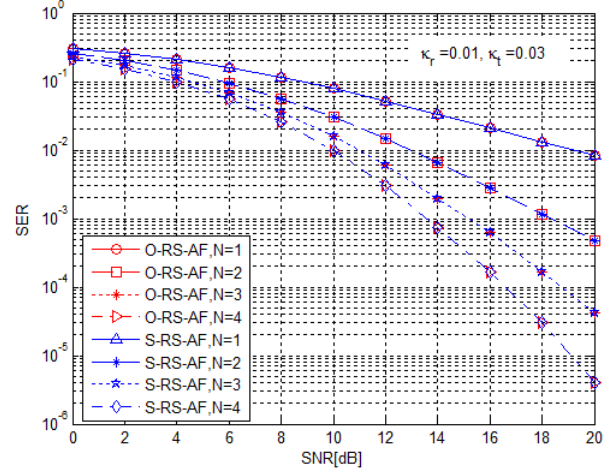


Fig. 2. Compare simulated SEP performance between optimal and sub-optimal relay selection methods when $N=1;2;3;4$.

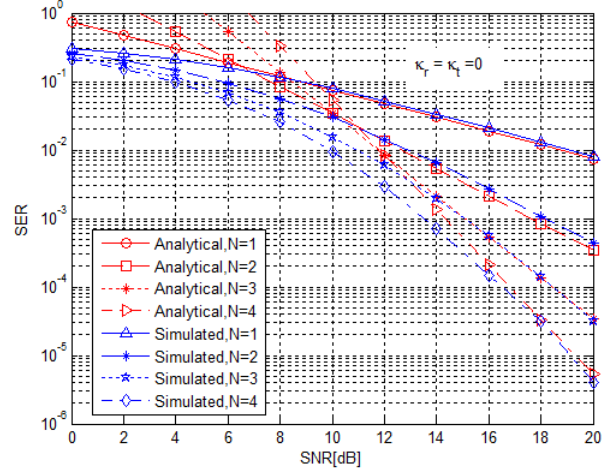


Fig. 3. Compare Analytical and Simulated SEP by the proposed S-RS-AF scheme when the relay hardware is ideal $\kappa_r = \kappa_t = 0$ and $N = 1; 2; 3; 4$

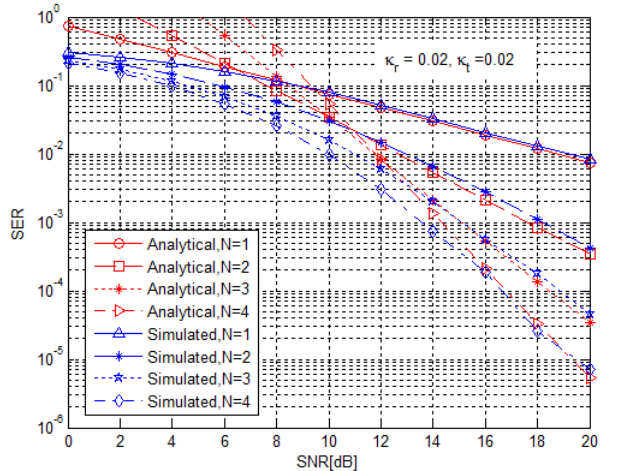


Fig. 4. Compare Analytical and Simulated SEP by the proposed S-RS-AF scheme, where $\kappa_r = \kappa_t = 0.02$ and $N = 1; 2; 3; 4$

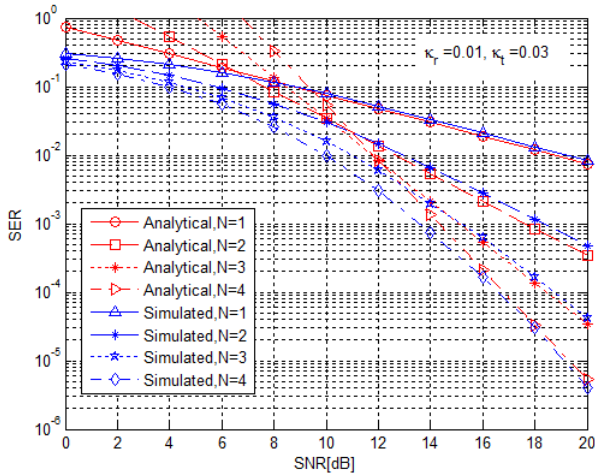


Fig. 5. Compare Analytical and Simulated SER by the proposed S-RS-AF scheme, where $\kappa_r = 0.01$, $\kappa_t = 0.03$ and $N = 1; 2; 3; 4$

is improved when SNR goes high and when number of the relays increase.

Figure 3 compare the simulated SEP using S-RS-AF with the asymptotic analytical SEP using theorem (1), the impairment level is $\kappa_r = \kappa_t = 0$. This occurs when the hardware is ideal and the simulation has the same result as [7].

With $\kappa_r = \kappa_t = 0.02$ we have the comparison in figure 4. Figure 5 demonstrates another case where the relay hardware isn't symmetric, $\kappa_r = 0.01$, $\kappa_t = 0.03$. Figure 3, 4 and 5 show that with high SNR and low hardware impairment level of relay transceiver, the analytical SEP is converged to the simulated result.

V. CONCLUSIONS

In this paper, we research the Relay Selection Method of two-way relaying network. But don't like in [7], this paper compute the effect of relay hardware transceiver and also find in which conditions the asymptotic SEP equation is still can be used.

This paper show that, we can use the Min-Max Relay Selection method as proposed in [7] even when it has the presence of hardware impairment of relays. The result of theorem (1) is more general than the asymptotic result in [7], because the parameter of hardware impairment level is considered. When we use ideal relay hardware, the result of theorem (1) has the same analytical result of [7].

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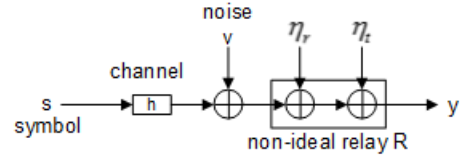


Fig. 6. Hardware impairment model

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APPENDIX A

TRANSCIEVER HARDWARE IMPAIRMENT MODEL

Consider an information symbol $s \in \mathbb{C}$ is transmitted over a wireless channel $h \in \mathbb{C}$ with additive noise $v \in \mathbb{C}$. The received signal is modeled as $y = hs + v$. Because of impairments, the transceivers make: i) the received signal distort during reception processing. ii) generate mismatch between the intended symbol s and actually signal emitted. From [8], [12], the generalized impairment model can be with distortion noises and the received signal is:

$$y = h(s + \eta_t) + \eta_r + v \quad (22)$$

while η_t, η_r are distortion noises from impairments of the transceiver.

And we also have η_t, η_r are Gaussian distribution

$$\eta_t \sim \mathcal{CN}(0, \kappa_t^2 P), \quad \eta_r \sim \mathcal{CN}(0, \kappa_r^2 P |h|^2) \quad (23)$$

P is average symbol power $P = \mathbb{E}_s\{|s|^2\}$, $\kappa_t, \kappa_r \geq 0$ are impairment level of transmitter and receiver hardware. When $\kappa_t = \kappa_r = 0$ (it mean ideal hardware), (23) reduce to classical form of received signal $y = hs + v$.