System Performance Analysis of Half-Duplex Relay Network over Rician Fading Channel

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Abstract

In this paper, the system performance of an amplify-and-forward (AF) relaying network over Rician Fading Channel is proposed, analyzed and demonstrated. For details this analysis, the energy and information are transferred from the source to the relay nodes by two methods: 1) time switching protocol and 2) power splitting protocol. Firstly, due to the constraint of the wireless energy harvesting at the relay node, the analytical mathematical expressions of the achievable throughput and the outage probability of both schemes were proposed and demonstrated. After that, the effect of various system parameters on the system performance is rigorously studied with closed-form expressions for the system performance. Finally, the analytical results are also demonstrated by Monte-Carlo simulation in comparison with the closed-form expressions. The numerical results demonstrated the effect of various system parameters, such as energy harvesting time, power splitting ratio, source transmission to noise power, and the threshold value, on the system performance of AF wireless relay nodes. The results show that the analytical mathematical and simulated results match for all possible parameter values for both schemes.

Keywords: amplify-and-forward (AF), relay network, throughput, outage probability, wireless energy harvesting (EH)

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1. Introduction

In the last decades, the proliferation of cellular networks and wireless sensor networks, have demanded the higher quality of power supply from the source node to wireless devices. In the conventional method, wireless devices are generally powered by batteries, which have to be replaced/recharged on time manually. In the communication network, the process battery replacement can be linked to some disadvantages such as inconvenient, infeasible for some applications [1-4]. In the last few years, wireless energy transfer (WET) technologies by supplying continuous and stable energy over the air is a proposed solution for avoiding disadvantages. This method could significantly reduce the maintenance cost and the frequency of energy outage events due to battery depletion. One of the best ways to transfer energy in the communication network is using RF signals. For wireless energy harvesting using RF signals, there are two main approaches to practice. The first solution is simultaneous wireless information and power transfer (SWIPT). On the second approach, the separated information decoding and energy harvesting receiver for information and power transfer is proposed, and it is named wireless powered communication network (WPCN). In comparison with the second method, the first method is not standard used in practice because of practical circuits for harvesting energy from RF signals are not yet able to decode the carried information directly [5-7].

In the last decades, there are many works focused on the WPCN solution. Such as some papers presented the process energy harvesting through the RF signals in cooperative wireless networks by a MIMO relay system the difference between the energy transfer and the information rates to provide the optimal source and relay precoding [8-10]. In the literature of the others, the authors investigated multi-user and multi-hop systems for simultaneous information
and power transfer with a dual-hop channel with an energy harvesting relay; the transmission strategy depends on the quality of the second link [11-13]. In these previous papers, the authors only focused on the WPCN with using the Rayleigh fading channels. i.e., the channel gains are assumed to be involved Gaussian random variables with zero means. However, in practice, the wireless channels are often found to be Gaussian distributed with non-zero mean, i.e., Rician fading channel [15-21]. However, there are not many works concentrate on the Rician fading channel yet, and the outage performance analysis of such channels is fundamental to practice. The remaining gap can fill by this work.

In this work, the system performance, in the term the achievable throughput and the outage probability, of an amplify-and-forward (AF) relaying network over Rician Fading Channel is proposed, analyzed and demonstrated in details. For details this analysis, the energy and information are transferred from the source to the relay nodes by two methods: 1) time switching protocol (TSP) and 2) power splitting protocol. In TSP, the fraction of the time interval is used for energy harvesting at the relay from the source signal, and the remaining time is used as follows: half of that for from the source to the relay information transmission, and the remaining half for the relay to destination information transmission. On another way, during the first half of the interval time, the fraction of the received signal power is used for energy harvesting and the remaining received power is used for transmitting source information to the relay node in the remaining half-time in PSP. The main contributions of the paper are summarized as follows:

1) The system model of the half-duplex relaying network over the Rician fading channels is proposed with the PSP and TSP.
2) The closed-form of the outage probability and throughput for the system is derived.
3) The influence of the main parameters on the system performance is demonstrated entirely.
4) The optimal power splitting and time switching factors is investigated and calculated in connection with the main system parameters.

The structure of this paper is proposed as follows. Sections II presents the system model of the amplify and forward (AF) relaying network over Rician Fading Channel. Sections III proposed the time switching and power splitting protocols in term of the achievable throughput and the outage probability, respectively. Section IV provides the numerical results and some discussions. Finally, Section V concludes the paper.

2. System Model

In this section, AF relaying cooperative network is presented in Figure 1. In Figure 1, the information is transferred from the source (S) to the destination (D), through an energy constrained intermediate relay (R). For energy harvesting and information processing at the relay by the time switching protocol is presented in Figure 2. In this scheme, T is the block time in which the source fully transmit the information data to the destination. In this time, \( \alpha T, \alpha \in (0, 1) \), is the time in which the relay harvests energy from the source signal, and \( (1 - \alpha)T \), is used for information transmission in such a way that half of that, \( (1 - \alpha)T/2 \), is used for the source to relay information transmission and the remaining half, \( (1 - \alpha)T/2 \), is used for the relay to destination information transmission. Furthermore, the energy harvesting and information processing at the relay by the power splitting protocol is proposed in Figure 3. Where P is the received signal power and T is the block time (Figure 3). Half of the time, \( T/2 \) is used for the source to relay information transmission and the remaining half, \( T/2 \) is used for the relay to destination information transmission. During the first half, the fraction of the received signal power, \( \rho P \) is used for energy harvesting and the remaining received power, \( (1 - \rho)P \) is used for transmitting source information to the relay node, where \( \rho \in (0, 1) \) [17-20]. More details of the analytical mathematical model of the achievable throughput and outage probability over Rician Fading Channel (for the time switching and power splitting protocol) is presented in the following sections [6-8].
Figure 1. System model

![System model diagram]

Figure 2. The time switching protocol

**3. The System Performance**

Based on the system model on above section, the system performance of the relay network is presented, analyzed and demonstrated with the time switching and power splitting protocols in details in this section [10-13].

**3.1. The Time Switching Protocol (TSP)**

Figure 2 presents the key parameters in the time switching protocol for energy harvesting and information processing at the relay. Here the energy harvesting and information processing at the relay node is presented. The received signal at the relay node is given by:

\[
y_{r}^{TS} = h_{SR}x_{s} + n_{r}
\]

(1)

The received signal at the destination is calculated as:

\[
y_{d}^{TS} = h_{RD}x_{r} + n_{d}
\]

(2)

The harvested energy during energy harvesting time \(\alpha T\) at the relay node is given by:

\[
E_{h}^{TS} = \eta P_{s} |h_{SR}|^{2} \alpha T
\]

(3)

Where \(\eta\) is the energy conversion efficiency (0 < \(\eta<1\)), and \(\mathbb{E}\{|x_{r}|^{2}\} = P_{s}\), \(\mathbb{E}\{\cdot\}\) is the expectation operator and \(|\cdot|\) is the absolute value operator.

The transmitted power from the relay node is given by:

\[
P_{r}^{TS} = \frac{E_{h}}{(1-\alpha)T/2} = \frac{\eta P_{s} |h_{SR}|^{2} \alpha T}{(1-\alpha)T/2} = \frac{2\eta \alpha P_{s} |h_{SR}|^{2}}{1-\alpha} = \zeta P_{s} |h_{SR}|^{2}
\]

(4)

In equation (4) we set \(\zeta = \frac{2\eta \alpha}{1-\alpha}\) and amplify factor: \(\beta = \frac{x_{r}^{TS}}{y_{r}^{TS}} = \frac{\sqrt{P_{r}^{TS}}}{\sqrt{P_{s} |h_{SR}|^{2} + N_{0}}}\).

The final form of received signal at the destination node is expressed by:

\[
y_{d}^{TS} = h_{RD}x_{r} + n_{d} = h_{RD}\beta y_{r}^{TS} + n_{d} = h_{RD}\beta|h_{SR}x_{r} + n_{r}| + n_{d}
\]

(5)
The received signal at the destination:

\[ y_d^{TS} = h_{SR}^2 \beta h_{RD} x + h_{RD}^2 \beta h_n + n_d \]

Here \( E \left( x_i^2 \right) = P_R \)  \( (6) \)

The end to end signal to noiseratio (SNR) at the destination node is given by (7):

\[ \gamma_{SD}^{TS} = \frac{E (\text{signal})^2}{E (\text{noise})^2} = \frac{|h_{SR}|^2 \beta^2 |h_{RD}|^2 P_i}{|h_{RD}|^2 N_0 + |h_{RD}|^2 N_0} = \frac{|h_{SR}|^2 |h_{RD}|^2 P_i}{|h_{RD}|^2 N_0 + \frac{N_0^2}{P_R} + N_0} \]

Because \( N_0 < < P_R \) so \( \gamma_{SD}^{TS} \) is closed by:

\[ \gamma_{SD}^{TS} \approx \frac{|h_{SR}|^2 |h_{RD}|^2 P_i}{|h_{RD}|^2 N_0 + \frac{N_0}{\zeta}} = \frac{\zeta |h_{SR}|^2 |h_{RD}|^2 P_i}{|h_{RD}|^2 N_0 + \frac{N_0}{\zeta}} = \frac{\zeta \rho_{SR} \rho_{PD} P_i}{\zeta \rho_{2} + 1} \]

(8)

In the equation (8) we denote that \( \varphi_1 = |h_{SR}|^2 \), \( \varphi_2 = |h_{RD}|^2 \), \( \gamma_0 = \frac{P_i}{N_0} \).

The probability density function (PDF) of random variable (RV) \( \varphi_i \) \( [19] \), where \( i = 1,2 \) is given by:

\[ f_{\varphi_i}(x) = \frac{(K+1)e^{-K}}{\lambda_i} e^{-\frac{(K+1)x}{\lambda_i}} I_0 \left( 2 \frac{K(K+1)x}{\lambda_i} \right) \]

(9)

Where \( \lambda_i \) is the mean value of RV \( \varphi_i \) which \( i = 1,2 \) respectively.

Moreover, \( K \) is the Rician K-factor defined as the ratio of the power of the line-of-sight (LOS) component to the scattered components and \( I_0(*) \) is the zero-th order modified Bessel function of the first kind.

The equation (11) can be rewritten as follows:

\[ f_{\varphi_i}(x) = \sum_{i=0}^{\infty} \left( \frac{bK}{(l!)^2} \right)^l x^l e^{-bx} \]  

(10)

Where \( a = \frac{(K+1)e^{-K}}{\lambda_i}, b = \frac{K+1}{\lambda_i} \) and \( I_0(x) = \sum_{l=0}^{\infty} \frac{x^{2l}}{(2l)!} \) could be get from \( [22] \).

The cumulative density function (CDF) of RV \( \varphi_i \), where \( i = 1,2 \) can be computed in \( [11] \) Here, we assume that \( \lambda_1 = \lambda_2 \)

\[ F_{\varphi_i}(\zeta) = \int_0^{\zeta} f_{\varphi_i}(x)dx = 1 - \frac{a}{b} \sum_{i=0}^{\infty} \sum_{m=0}^{i} \frac{K^i b^m}{i! m!} e^{-bc} \]

(12)

Proposition 1: The outage probability at a fixed source transmission rate R is:

\[ P_{out} = F_{\gamma_{SD}}(\gamma_{th}) = \Pr \left( \gamma_{SD}^{TS} < \gamma_{th} \right) = \Pr \left( \frac{\zeta \rho_{SR} \rho_{PD} \gamma_0}{\zeta \rho_{2} + 1} < \gamma_{th} \right) \]

(13)
Where \( \gamma_{th} = 2^R - 1 \) is the th SNR threshold value, \( R \) is source rate value.

Finally, throughput at the destination node can be given by:

\[
\tau_{TS} = (1 - P_{out}) \frac{(1 - \alpha)R}{2}
\]  

(14)

### 3.2. The Power Splitting Protocol (PSP)

Figure 3 shows the communication block diagram employing the PSR protocol for energy harvesting and information processing at the relay node. Here the energy harvesting and information processing at the relay node for the power splitting protocol is proposed. Similar as time switching protocol we have:

\[
y_{PS}^s = \sqrt{1 - \rho} h_{Sr} x_s + n_s
\]  

(15)

\[
y_{PS}^d = h_{Dr} x_r + n_d
\]  

(16)

\[
E_{PS}^R = \eta \rho (T/2) P_s |h_{Sr}|^2
\]  

(17)

\[
P_{RPS}^T = E_{PS}^R = \eta \rho P_s |h_{Sr}|^2
\]  

(18)

In this section, amplify factor as \( \kappa = \frac{x_r}{\gamma^r_{PS}} = \sqrt{\frac{P_{RPS}^T}{(1 - \rho) P_s |h_{Sr}|^2 + N_0}}. \)

\[
y_{PS}^d = h_{Dr} x_r + n_d = h_{Dr} \kappa y_{PS}^s
\]  

(19)

\[
y_{PS}^{sd} = \frac{E\{(\text{signal})^2\}}{E\{(\text{noise})^2\}} = \frac{|h_{RD}|^2 (1 - \rho) |h_{SR}|^2 P_s}{|h_{RD}|^2 N_0 + \frac{\eta \rho P_s |h_{SR}|^2 + N_0}{P_{RPS}^T}}
\]  

(20)

Using the fact that \( N_0 << P_R \) and using (26) so we have:

\[
y_{PS}^{sd} = \frac{(1 - \rho) \phi_l \phi_m P_{RPS}^T}{\phi_l N_0 + \frac{N_0 (1 - \rho)}{\eta \rho} + \frac{\eta \rho \phi_l \phi_m y_{0}}{1 - \rho} + 1}
\]  

(21)

Where \( \mu = \frac{\eta \rho}{1 - \rho} \). The outage probability at the destination node is given by:

\[
P_{out} = F_{\gamma_{SD}}(\gamma_{th}) = \Pr\left(y_{PS}^{SD} < \gamma_{th}\right) = 1 - \frac{2a^2}{\mu \eta \rho} e^{-\frac{b_{Y_{th}}}{\mu \eta \rho}}
\]  

(22)

Finally, the at the destination node:

\[
\sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{K_{l+k+m+k-l}}{l!m!(m-n)!(k)!} \left( \frac{\gamma_{th}}{\gamma_0} \right)^{l+k+m-k} \left( \frac{1}{(1-\rho)^{m-n}} \times \frac{1}{\eta \rho \phi_l \phi_m \gamma_0} \right) \times K_{k-n-l} \times \left( b_{Y_{th}} \right)^2 \frac{\gamma_{th}}{\eta \rho \gamma_0}
\]  

(22)
\[ \tau_{PS} = (1 - P_{out}) \frac{R}{2} \]  

(23)

Where \( K_v(\bullet) \) is the modified Bessel function of the second kind and \( v \)th order.

### 3.3. Optimal Power Splitting Factor

The optimal value \( \rho^* \) or \( \alpha^* \) can be obtained by solving the equation \( \frac{d\tau(\rho)}{d\rho} = 0 \) and \( \frac{d\tau(\alpha)}{d\alpha} = 0 \). Given the throughput expression in (12) and (23), this optimization problem does not admit a closed-form solution. However, the optimal \( \rho^* \) or \( \alpha^* \) is efficiently solved via numerical calculation, as illustrated below. Here, we can use Golden section search algorithm to find the optimal factor \( \rho^* \) and \( \alpha^* \). This algorithm has been used in many global optimization problems in communications, for example, in [23]. The detailed algorithm as well as the related theory is described in [24].

### 4. Numerical Results and Discussion

In this section, the throughput performance and the outage probability of an energy harvesting AF relaying network over Rician Fading Channel are analyzed in details. The system performance in term of the throughput performance and the outage probability is analyzed in connection with \( \alpha, \rho, P_s/N_0 \) and \( R \). We consider a network with one source, one relay, and one destination, where source-relay and relay-destination distances are both normalized to unit value.

In Figure 4 and 5, the effect of \( \alpha \) (0 \( \leq \alpha < 1 \)) for the time switching protocol and \( \rho \) (0 \( \leq \rho < 1 \)) for the power splitting protocol on the achievable throughput and the outage probability of the AF relay network system is presented. From Figure 4 and 5, the analytical and the simulation results match for all possible values of \( \alpha \) and \( \rho \) for both the time switching and the power splitting protocols. Figure 4 shows that the throughput increases as \( \alpha \) and \( \rho \) increases from 0 to some optimal \( \alpha \) and \( \rho \) but later, it starts decreasing as \( \alpha \) and \( \rho \) increases from its optimal value. When the values of \( \alpha \) smaller than the optimal \( \alpha \), there is less time for energy harvesting. Consequently, less energy is harvested and smaller values of throughput are observed at the destination node due to larger outage probability. On the other hand, for the values of \( \alpha \) greater than the optimal \( \alpha \), more time is wasted on energy harvesting and less time is available for information transmission. This is because for the values of \( \rho \) smaller than the optimal \( \rho \), there is less power available for energy harvesting. Consequently, less transmission power \( P_s \) is available from the relay node and smaller values of throughput are observed at the destination node due to larger outage probability. On the other hand, for the values of \( \rho \) greater than the optimal \( \rho \) (0.6), more power is wasted on energy harvesting and less power is left for the source to relay information transmission.

Furthermore, Figure 6 and 7 plot the influence of the ratio \( P_s/N_0 \) on the achievable throughput and the outage probability at the destination node. The achievable throughput increases and the outage probability decreases significantly at the destination node for the time switching protocol while the ratio \( P_s/N_0 \) varies from 0 to 30 dB. In the similar, the achievable throughput increases and the outage probability decreases significantly at the destination node for the power splitting protocol while the ratio \( P_s/N_0 \) varies from 0 to 30 dB (Figure 8 and 9). It can be prove by the opinion that the strength of the RF signal increases in the direction of increasing the power of the source signals and decreasing the noise interference.

In Figure 10 and 11, the optimal throughput and the outage probability for the time switching and the power splitting protocols is proposed with different values of the source transmission rate, \( R \) bits/sec/Hz. Figure 10 shows that the achievable throughput increases as \( R \) increases to a specific value but then starts decreasing for larger values of \( R \). On the other hand, for more great transmission rates \( R \), the receiver fails to correctly decode a significant amount of data in the limited time. Thus, the outage probability increases and the throughput decreases (Figure 11).
Figure 4. The throughput for different values of $\alpha$ and $\rho$

Figure 5. The outage probability for different values of $\alpha$ and $\rho$

Figure 6. The throughput for different values of ratio $P_s/N_0$ for time switching protocol
Figure 7. The outage probability for different values of ratio $P_s/N_0$ for time switching protocol

Figure 8. The throughput for different values of ratio $P_s/N_0$ for power splitting protocol

Figure 9. The outage probability for different values of ratio $P_s/N_0$ power splitting protocol
Figure 10. The throughput for different values of source transmission rate R

Figure 11. The outage probability for different values of source transmission rate R

Figure 12. The outage probability for different values of source transmission rate R
4. Conclusion

In this paper, an amplify-and-forward wireless cooperative network over Rician Fading Channel with the time switching and the power splitting protocols has been considered. In order to analyze the system performance at the destination, analytical expressions for the outage probability and the throughput are proposed. The numerical analysis in this paper has provided practical insights into the effect of various system parameters on the system performance of AF relay nodes over Rician Fading Channel. The results show that the analytical mathematical and simulated results match for all possible parameter values for both schemes. The results could be provide the prospective solution for the communication network in the near future.

References


