The Wireless Information System and the Decode and Forward Relay

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ABSTRACT: *We have studied the wireless information system and the decode and forward relay. The outage probability performance in mixed Rician and shadowing fading channels is determined, for the scenario when relay harvests energy and time-switching (TS) scheme is applied. In addition, the closed-form tight asymptotic outage expression is derived. We have further studied the energy harvesting ratio, line-of-sight (LoS), shadowing components and fading parameters on outage probability.*

Keywords: Decode-and-forward Relay, Energy Harvesting, Outage Probability, Rician Fading, Time Switching Scheme

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1. Introduction

Energy harvesting technique has recently occupied a special place in research area, as an efficient solution for powering wireless communication devices. In contrast to natural energy sources (wind, solar, etc.) which are depended on weather conditions and cannot be used indoors, the sources of radio frequency (RF) energy are omnipresent and controllable. Moreover, RF signals are able to simultaneously transfer both information and energy, which is an additional justification for the widely investigated application of this technique [1-4].

Since the receiver is unable to perform energy harvesting and information signal processing at the same time, two concepts of receiver schemes are usually adopted: time switching (TS) and power splitting (PS). In TS-based scheme, one part of time is used to harvest energy at the relay, while the rest of time is dedicated for the decoding and transmission. On the other hand, in the PS-based receiver architecture, one part of received power is utilized for harvesting, while the remaining power is used for signal processing [4].

The simultaneous wireless transfer of information and power is applied in both relay and sensor networks, which are used to expand the signal coverage area providing the same quality of service and improve signal transmission [3-4]. In the scenarios where it is not possible to provide direct communication between transmitter and receiver, relays are used to enable communication between them. In order to improve system performances, it is desirable to provide line-of-sight (LoS) between source and relay node. In [5], the multi-user system over Rician distributed fading channel was studied, considering opportunistically harvesting PS scheme.

Moreover, dual-hop system in mixed Rician and Rayleigh fading scenario with energy harvesting amplify-and-forward (AF) relay and PS scheme was analyzed in [6] and [7]. The impact of LoS path effect on the outage probability is investigated in [6], for the case when only one user destination node exists, while AF multiuser system is considered in [7]. The minimization of outage performances based on power allocation, relay placement and PS for dual-hop decode-andforward (DF) system over Rician fading channels is analyzed in [8].

In this paper, we analyze dual-hop relaying system, where DF relay is powered by RF energy harvested from source node based on TS scheme. The relay position is determined such that LoS is provided between source and relay nodes, and the first hop is affected by Rician fading. The second hop is influenced by the simultaneous existence of multipath fading and shadowing effects, which are modeled by generalized-*K* (Gamma-Gamma) distribution due to mathematical tractability [9]. For the considered scenario the outage probability expression is determined in the integral form and various effects of LoS and shadowing components are investigated. Furthermore, the approximative expression is derived in the exact closed-form. Numerical results has been obtained and shown excellent agreement between exact and approximate results in high average signal-to-noise (SNR) on the second hop regime. Monte Carlo simulations are presented to confirm derived analytical expressions.

2. System and Channel Model

2.1 System Model

We consider the DF relay system where direct link between the source and the destination is not available due to obstacles and/or deep fading. In order to establish connection between the destination nodes, the position of the relay is determined such that the LoS between the source and the relay exists. The source transmits information to a destination via DF relay, which also harvest RF energy based on the time-switching scheme. The total communication time slot T is divided into two parts, based on energy harvesting ratio value α. In the first time interval αT, relay harvests energy, and the remaining time $(1-\alpha)T$ is used for information transmission from the source to the relay and from the relay to the destination (this interval is divided into two equal parts) [4].

The source transmits signal x with power P_S. If we denote the channel fading gain from the source to the relay by h_{SR}, the received signal at the relay is given with

$$y_R = \sqrt{P_S}\, h_{SR} x + n_R\,, \tag{1}$$

where n_R is the additive white Gaussian noise (AWGN) at the relay with variance σ^2_R. As the relay harvests energy during the time interval αT, the harvested energy at the relay is $E_H = \eta P_S |h_{SR}|^2 \alpha T,$ where η is the energy conversion efficiency coefficient. The output relay power is obtained as

$$P_R = \frac{2\eta\alpha}{\left(1-\alpha\right)} P_S \left|h_{SR}\right|^2 \tag{2}$$

The relay transmits signal x_R to the destination, and the channel fading gain form the relay to the transmitter is h_{RD}. The received signal at the destination is given by

$$y_D = \sqrt{P_R}\, h_{RD} x_R + n_D \tag{3}$$

where n_D is AWGN at the destination with variance σ^2_D.

2.2 Source-Relay Channel

We assume that the position of the relay enables signal propagation with the LoS between the source and the relay. The source sends information to the relay and also enables energy for signal transmission from the relay to the destination. It is assumed that fading over source-relay channel follows Rician distribution [10]. As the signal-to-noise ratio (SNR) is given with

$$\gamma_R = \frac{P_S \left| h_{SR} \right|^2}{\sigma_R^2} \tag{4}$$

the probability density function (PDF) of the instantaneous SNR at the relay is [10]

$$p_{\gamma_R}(\gamma) = \frac{(K+1)e^{-K}}{\bar{\gamma}_{SR}} e^{-\frac{(K+1)\gamma}{\bar{\gamma}_{SR}}} I_0\left(2\sqrt{\frac{K(K+1)\gamma}{\bar{\gamma}_{SR}}}\right) \tag{5}$$

where K denotes the Rician K factor (equal to the ratio of the power of the LoS component to the average power of the scattered component), $\bar{\gamma}_{SR} = E\,[\gamma^2_R]$ is the average SNR at the relay and $I_{0(x)}$ is the zero-th order modified Bessel function of the first kind [11, Eq. 8.431.1].

The corresponding cumulative distribution function (CDF) is given by [10]

$$F_{\gamma_R}(\gamma) = 1 - Q\left(\sqrt{2K}, \sqrt{\frac{2(1+K)\gamma}{\bar{\gamma}_{SR}}}\right) \tag{6}$$

where $Q(x)$ is the first-order Marcum Q-function [10].

2.3 Relay-Destination Channel

We assumed that the environment from the relay to the destination is such that it can be considered that in addition to fading in the channel, the shadowing effect exists. The phenomenon of multipath fading is modeled by Nakagami PDF and the variation of the average power (as a result of shadowing effect) follows Gamma PDF [9]. Therefore, the PDF of composite generalized K fading is given by

$$\begin{aligned} p_{|h_{RD}|^2}(\gamma) = {} & \frac{2}{\Gamma(m_m)\Gamma(m_s)} \left(\frac{m_m m_s}{\bar{\gamma}_{RD}}\right)^{\frac{m_m+m_s}{2}} \\ & \times \gamma^{\frac{m_m+m_s}{2}-1} K_{m_s-m_m}\left(2\sqrt{\frac{m_m m_s}{\bar{\gamma}_{RD}}\gamma}\right) \end{aligned} \tag{7}$$

where m_m is Nakagami-m multipath fading parameter, m_s is the shadowing parameter, $\bar{\gamma}_{RD} = E\,[h^2_{RD}]$ is the average SNR and $K_{u(x)}$ is modified Bessel function of the second kind [11, Eq. 8.432.3]. The corresponding CDF is

$$F_{|h_{RD}|^2}(\gamma) = \frac{1}{\Gamma(m_m)\Gamma(m_s)} G^{2,1}_{1,3}\left(\frac{m_m m_s \gamma}{\bar{\gamma}_{RD}} \middle| \begin{matrix} 1 \\ m_s, m_m, 0 \end{matrix}\right) \tag{8}$$

where $G^{p,q}_{m,n}\left(x \middle| \begin{matrix} a_r \\ b_s \end{matrix}\right)$ is Meijer G-function [11, Eq. 9.301].

Finally, using (2), the instantaneous SNR at the destination node, can be determined as

$$\begin{aligned}\gamma_D &= \frac{2\eta\alpha}{\left(1-\alpha\right)\sigma_D^2} P_S \left|h_{SR}\right|^2 \left|h_{RD}\right|^2 \\ &= \frac{2\eta\alpha\sigma_R^2}{\left(1-\alpha\right)\sigma_D^2} \gamma_R \left|h_{RD}\right|^2 = c\gamma_R \left|h_{RD}\right|^2\end{aligned} \tag{9}$$

where $c = \frac{2\eta\alpha\sigma_R^2}{\left(1-\alpha\right)\sigma_D^2}$.

3. Outage Performance

The outage probability is important performance measure, defined as the probability that the instantaneous equivalent SNR of dual-hop system, falls below a predetermined protection value, γ_{th} [10]. In the considered DF relay system, the outage probability can be determined as

$$P_{out} = P_r\left\{\gamma_R \le \gamma_{th}\right\} + P_r\left\{\gamma_D \le \gamma_{th}, \gamma_R > \gamma_{th}\right\}, \tag{10}$$

and also written in the equivalent form

$$\begin{aligned}P_{out} &= F_{\gamma_R}\left(\gamma_{th}\right) + P_r\left\{\left|h_{RD}\right|^2 \le \frac{\gamma_{th}}{c\gamma_R}, \gamma_R > \gamma_{th}\right\} \\ &= F_{\gamma_R}\left(\gamma_{th}\right) + \int_{\gamma_{th}}^{\infty} F_{\left|h_{RD}\right|^2}\left(\frac{\gamma_{th}}{c\gamma_R}\right) p_{\gamma_R}\left(\gamma_R\right) \mathrm{d}\gamma_R\end{aligned} \tag{11}$$

By using the infinite-series representation of $I_0(.)$ [11, Eq. 8.447.1], the outage probability can be re-written in the following form

$$\begin{aligned}P_{out} &= F_{\gamma_R}\left(\gamma_{th}\right) + \frac{\left(K+1\right)\mathrm{e}^{-K}}{\Gamma\left(m_m\right)\Gamma\left(m_s\right)\overline{\gamma}_{SR}} \sum_{i=0}^{\infty} \frac{1}{\left(i!\right)^2}\left(\frac{K\left(K+1\right)}{\overline{\gamma}_{SR}}\right)^i \\ &\times \int_{\gamma_{th}}^{\infty} \gamma_R^i G_{1,3}^{2,1}\left(\frac{m_m m_s \gamma_{th}}{\overline{\gamma}_{RD} c\gamma_R}\middle|\begin{matrix}1\\ m_s, m_m, 0\end{matrix}\right) \mathrm{e}^{-\frac{\left(K+1\right)\gamma_R}{\overline{\gamma}_{SR}}} \mathrm{d}\gamma_R\end{aligned} \tag{12}$$

After substituting $t = \gamma_R - \gamma_{th}$ in (12) and applying binomial theorem the outage probability is determined as

$$\begin{aligned}P_{out} &= F_{\gamma_R}\left(\gamma_{th}\right) + \frac{\left(K+1\right)\mathrm{e}^{-K}}{\Gamma\left(m_m\right)\Gamma\left(m_s\right)\overline{\gamma}_{SR}} \sum_{i=0}^{\infty}\sum_{j=0}^{i}\binom{i}{j} \\ &\times \frac{\gamma_{th}^{i-j}}{\left(i!\right)^2}\left(\frac{K\left(K+1\right)}{\overline{\gamma}_{SR}}\right)^i \mathrm{e}^{-\frac{\left(K+1\right)\gamma_{th}}{\overline{\gamma}_{SR}}} \\ &\times \int_{0}^{\infty} t^j G_{1,3}^{2,1}\left(\frac{m_m m_s \gamma_{th}}{\overline{\gamma}_{RD} c\left(t+\gamma_{th}\right)}\middle|\begin{matrix}1\\ m_s, m_m, 0\end{matrix}\right) \mathrm{e}^{-\frac{\left(K+1\right)t}{\overline{\gamma}_{SR}}} \mathrm{d}t\end{aligned} \tag{13}$$

Unfortunately, we cannot find a closed-form analytical solution for the integral in (13). The outage probability given by (13) can be evaluated by numerical integration

However, for small argument value of Meijer G-function using [12, Eq. 07.34.06.0006.01], and $y = t/\gamma_{th}$, the approximation for the integral (13) can be determined in the exact closed-form. The approximate expression for the outage probability is derived in the following closed-form in the case when $m_m < m_s$

$$P_{out}^{m_m<m_s} \approx F_{\gamma_R}\left(\gamma_{th}\right) + \frac{\Gamma\left(m_s - m_m\right)}{m_m \Gamma\left(m_m\right)\Gamma\left(m_s\right)} \frac{\left(K+1\right)e^{-K}}{\overline{\gamma}_{SR}} \mathrm{e}^{-\frac{(K+1)\gamma_{th}}{\overline{\gamma}_{SR}}} \\ \times \left(\frac{m_m m_s}{\overline{\gamma}_{RD} c}\right)^{m_m} \sum_{i=0}^{\infty}\sum_{j=0}^{i} \binom{i}{j} \gamma_{th}^{i+1} \frac{\Gamma\left(1+j\right)}{\left(i!\right)^2} \\ \times \left(\frac{K\left(K+1\right)}{\overline{\gamma}_{SR}}\right)^{i} U\left(1+j, j-m_m+2, \frac{\left(K+1\right)\gamma_{th}}{\overline{\gamma}_{SR}}\right) \tag{14}$$

For the case when $m_m > m_s$, the approximate outage probability expression is given as

$$P_{out}^{m_s<m_m} \approx F_{\gamma_R}\left(\gamma_{th}\right) + \frac{\Gamma\left(m_m - m_s\right)}{m_s \Gamma\left(m_m\right)\Gamma\left(m_s\right)} \frac{\left(K+1\right)e^{-K}}{\overline{\gamma}_{SR}} e^{\frac{(K+1)\gamma_{th}}{\overline{\gamma}_{SR}}} \\ \times \left(\frac{m_m m_s}{\overline{\gamma}_{RD} c}\right)^{m_s} \times \sum_{i=0}^{\infty}\sum_{j=0}^{i} \binom{i}{j} \gamma_{th}^{i+1} \frac{\Gamma\left(1+j\right)}{\left(i!\right)^2} \\ \times \left(\frac{K\left(K+1\right)}{\overline{\gamma}_{SR}}\right)^{i} U\left(1+j, j-m_s+2, \frac{\left(K+1\right)\gamma_{th}}{\overline{\gamma}_{SR}}\right) \tag{15}$$

where *U(a,b;z)* is the confluent hypergeometric function of the second kind [11, eq. 9.211.4].

4. Numerical Results

In order to analyze the impact of LoS component and shadowing effects, the numerical results for dual-hop DF harvesting system with applied time-switching scheme are presented in this section. Numerical results are obtained and confirmed by independent Monte-Carlo simulation method. It has been demonstrated that the closed-form approximate expression tightly bounds the exact results.

In Figure 1. the influence of direct LoS component between source and relay is presented for various values of energy harvesting ratio α. For small values of Rician factor K, ratio of the total time dedicated for the energy harvesting, does not significantly affect outage performance if $\alpha > 0.3$. With the increase of factor K, the outage probability decreases, and the outage floor appears for large values of K parameter. The value of outage floor strongly depends on energy harvesting ratio. For example, by increasing energy harvesting ratio from 0.3 to 0.5, the outage performance is lower an order of magnitude.

The dependence of outage probability on the energy harvesting ratio α are presented in Figure 2. Also, the impact of the value of average second hop SNR is investigated. For the low values of energy harvesting ratio, the average second hop SNR has great influence on outage performances, but when α is increasing and tends to 1, the outage floor appears and the power of the second hop does not significantly affects outage performances. The preciseness of the approximation given by Eq. (15) is demonstrated by comparing with the numerical and simulation results. In accordance with the expectations, the approximation is more consistent with the exact and simulation curves when average second hop SNR has higher values (as it is was the condition for deriving the approximate expression).

Figure 3. shows outage probability dependence on average SNR for various shadowing conditions and different values of Rician K parameter. The outage probability decreases with the increase of average SNR in both hops. However, for small values of parameter K, the difference in outage probability performances for the observed propagation scenarios is diminishing. When propagation conditions in the first hop improve and LoS component increase, the influence of the second hop fading and shadowing effects is reflected on the system performance. In accordance to the expectations, the outage probability

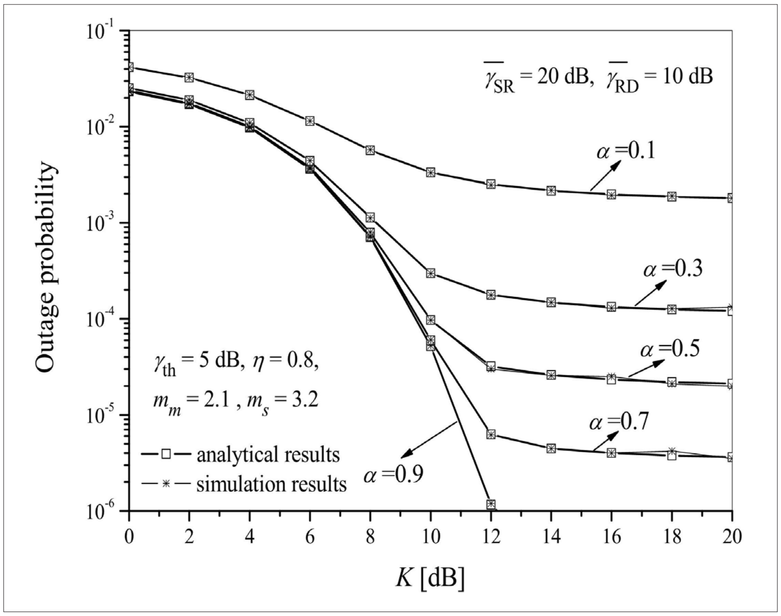

Figure 1. Outage probability versus Rician *K* factor for various values of energy harvesting ratio

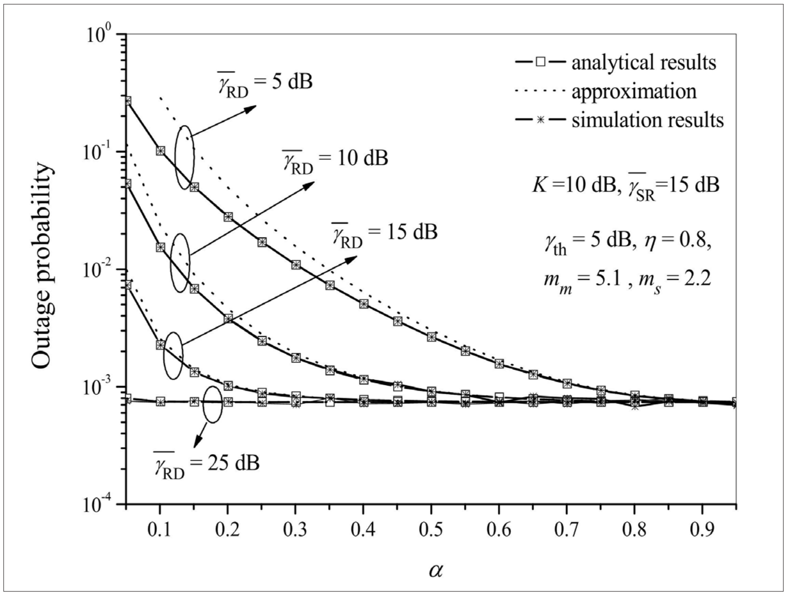

Figure 2. Outage probability versus energy harvesting ratio for various values of average SNR of second hop

decreases when the fading and shadowing effects over second hop are improved.

5. Conclusion

The outage performances of energy harvesting DF relaying system over Rician and shadowing fading channels has been analyzed in this paper. The TS scheme has been considered. The tight asymptotic outage expression has been derived in the exact closed-form. We have analyzed the impact of LoS component of the first hop, and shadowing conditions of the second hop on the outage probability performance. The excellent agreement among exact, asymptotic and simulation results has been observed.

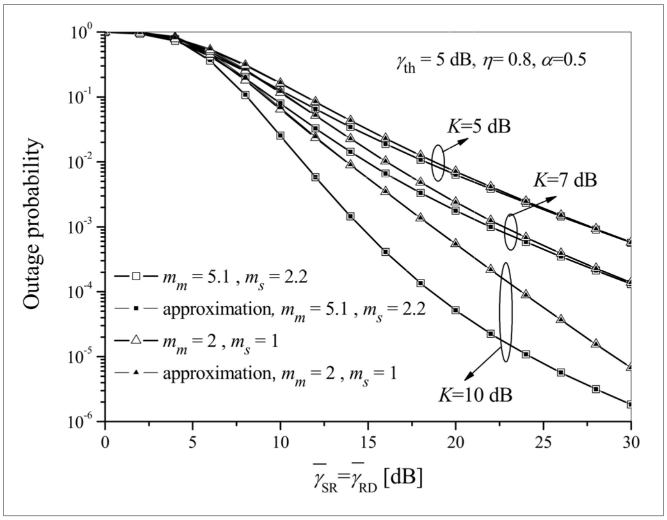

Figure 3. Outage probability versus average SNR for various fading and shadowing conditions

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