Performance of Amplify-and-Forward Relaying with Wireless Power Transfer over Dissimilar Channels

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***Abstract*—Relaying transmission is a promising approach for enhancing the performance of wireless networks, meanwhile wireless power transfer is an emerging solution for prolonging the lifetime of energy constrained relay nodes. In this framework, the amplify-and-forward (AF) relay network consisting of a power transfer and information source, an energy constrained relay and a destination over dissimilar fading channels is taken into account. First, the relay employs the time switching-based relaying (TSR) protocol to harvest energy from the source. Accordingly, the relay supports the source transmits information to the destination. By utilizing the statistical characteristics of signal-to-noise ratio (SNR), the closed-form expressions of outage probability (OP) and average symbol error probability (ASEP) are derived. By means of the obtained result of OP, we also investigate throughput of the system for delay-limited transmission mode. Moreover, we accordingly evaluate the analysis in details and assess the performance of the considered system in various system parameters, such as energy harvesting time, energy harvesting efficiency, and relay location. Finally, Monte-Carlo simulation is also contributed to confirm the correctness of the analytical results.**

***Index Terms*—Wireless power transfer, energy harvesting, amplify-and-forward, outage probability, average symbol error probability, throughput.**

I. INTRODUCTION

Radio frequency (RF) energy harvesting (EH), a technique to collect wireless energy from the surrounding environment for prolonging the lifetime of a wireless network, has received significant attention recently from both academia and industry [1]–[5]. Since the harvested energy is typical in a small amount and also random, it is difficult to satisfy short-term performance. Relay methodology has a great potential to increase the diversity that can improve the performance of wireless networks [6]–[9]. As a deduction, many researchers have paid attention on performance of EH relay networks in recent years [10]–[14].

For related prominent works, in [10], a cooperative system in which EH nodes volunteer evaluated as AF relays whenever they have sufficient energy for the transmission over frequency-flat, block-fading Rayleigh channels is considered. The closed-form expressions for the symbol error rate (SER) of the system and the asymptotic energy savings at the source from the exploit of EH relays are revealed. The analysis showed that the energy usage at an EH relay depends not only on the relay's energy harvesting process, but also on its transmit power setting and the other relays in the system. Chalise *et. al*. [11] deals with the performance limits of a two-hop multi-antenna AF relay system in the presence of a multi-antenna energy harvesting receiver. The source and relay nodes of the two-hop AF system employ orthogonal space-time block codes for data transmission. Moreover, the trade-offs in information rate and energy transfer were characterized by the boundary of solving joint source and relay precoder optimization problems. In the paper [13], the researchers investigated a wireless energy harvesting and information transfer protocol in cognitive relay networks over the quasi-static Rayleigh fading channels. The secondary transmitter harvests energy from the received primary signal and hence forwards the resulting signals along with the secondary signal. The secondary receiver can also collect the ambient energy, and processes the remaining signal to remove the primary interference. Following this scenario, they analytically derive the exact expressions of the outage probabilities for both primary and secondary networks. Based on the proposed protocol, they analysed the rate-energy trade-off between the maximum ergodic capacity and the maximum harvested energy in the secondary network. Taking into account the work [14], an AF cooperative network is considered, where an energy constrained relay node harvests energy from the received RF signals and then uses that harvested energy to forward the source signal to the destination node over Rayleigh fading channels. Analytical expressions for the outage probability and the ergodic capacity are inferred for the delay-limited and the delay-tolerant transmission modes.

Due to the movement of wireless devices, the channels of two hops may be subject to different fading property. Especially, in energy harvesting relay networks, the relay should be close to energy station. Therefore, the assumption of all above studies that the channels of two hops in energy harvesting relay networks are subject to the same fading

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property is weakened. Moreover, due to the relay is close to energy station, the line-of-sight (LOS) wave should exist between the source and the relay. There have been many works considering the heterogeneity fading characteristic between the channels in relay network appreciably, however, without the existence of EH scheme [6], [7].

In our paper, we focus on the performance of power transfer system consisting of a power and information source, an energy constrained relay and a destination that all of them are equipped with single antenna over dissimilar Rayleigh/Rician fading channels. The main contributions of this paper fall in the derivations of the closed-form expression of outage probability and average symbol error probability by utilizing statistical characteristics of the SNR. Additionally, by means of the result of OP, we carry out evaluating the throughput at the destination. Moreover, we also analyse the performance of the considered system in various system parameters, such as energy harvesting time, energy harvesting efficiency, and relay location.

The rest of this paper is organized as follows. Section II presents the system and channel model. Performance of the considered system is analysed in Section III. In Section IV, we show the numerical results. We conclude our work in Section V.

II. SYSTEM AND CHANNEL MODEL

We consider a two-hop AF communication system with energy harvesting illustrated in Fig. 1.

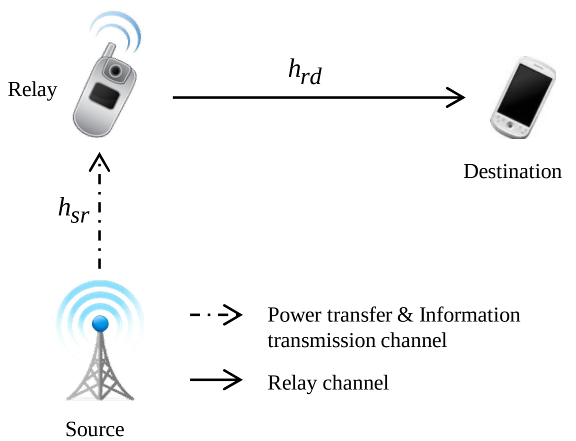

Fig. 1. System model for dual-hop relay networks with energy harvesting.

The network consists of one power transfer and information source denoted by *S*, one destination denoted by *D* and one energy constrained relay node denoted by *R*. In this paper, we consider the following scenario:

– Direct link between the source and the destination is not available due to this link is in poor transmission condition and the communication from *S* to *D* is performed by the help of relay *R*.

– Relay harvests energy from the power transfer source *S* and helps the source convey information to the destination by using the TSR protocol [12].

– The source transmits the power and information to the relay over Rician fading channel. Meanwhile, the relay amplifies the received signal and transmits information to destination over Rayleigh fading environment. This supposition is reasonable since the energy constrained relay node usually is close to the power transfer station. In fact, the channel between the source and relay has LOS, whereas the channel between the relay and destination might not necessarily be the same. Note that, Rician fading occurs when one of the paths, typically a LOS signal, is much stronger than the others. We also have supposed that in each block time *T*, these channels are constant and independently and identically distributed (i.i.d).

– All transmitters and receivers are equipped with a single antenna.

– Compared to the power used for signal transmission from the relay to the destination, the processing power required by the transmit/receive circuitry at the relay is insignificant. So it can be ignored.

First, the relay harvests energy from the power transfer source in the time duration of αT which are [14]

$$P_r = \frac{E_h}{(1-\alpha)T/2} = \frac{2\eta P_s |h_{sr}|^2 \alpha}{(1-\alpha)d_1^{\beta_1}} = aP_s\gamma_1, \qquad (1)$$

where $0 < \eta \le 1$ is the energy conversion efficiency which depends on the rectification process and the energy harvesting circuitry; P_S is the transmit power of the source; T is the block time in which a certain block of information is conveyed from the source node to the destination node; α is the fraction of the block time in which relay collects energy from the source signal, $0 < \alpha \le 1$. Considering the link from the source to relay, $|h_{sr}|^2$ is the channel power gain, d_1 is the distance, β_1 is the path-loss exponent; $a = \frac{2\eta\alpha}{(1-\alpha)}$, $\gamma_1 = \frac{|h_{sr}|^2}{d_1^{\beta_1}}$.

In the duration of $(1-\alpha)T/2$, the source transmits signal *x(t)* to the relay and the signal received at relay as follows

$$y(t) = \frac{\sqrt{P_s}h_{sr}}{\sqrt{d_1^{\beta_1}}}x(t) + n_r, \qquad (2)$$

where n_r is white complex Gaussian noise, $n_r \sim \mathcal{CN}(0, N_1)$.

In the remain duration of $(1-\alpha)T/2$, the relay amplifies the signal received from the source and retransmits to the destination. Assume that the channel coefficient h_{sr} is available to the relay. The received signal at destination is given by

$$z(t) = \sqrt{\frac{P_r}{\mathbf{E}\left(|y(t)|^2\right)}}\frac{h_{rd}}{\sqrt{d_2^{\beta_2}}}y(t) + n_d, \qquad (3)$$

where d_2 and β_2 are the distance and path-loss exponent from the relay to the destination, respectively. n_D is white complex Gaussian noise, $n_d \sim \mathcal{CN}(0, N_2)$. For simplicity, we suppose $N_1 = N_2 = N_0$; $\mathbf{E}(\bullet)$ is expectation operator.

We rewrite *z(t)* as

$$z(t)=\sqrt{\frac{P_rP_s}{\frac{P_s\,|h_{sr}|^2}{d_1^{±1}}+N_0}}\frac{h_{sr}h_{rd}}{\sqrt{d_1^{±1}d_2^{±2}}}x(t)+$$
$$+\sqrt{\frac{P_r}{\frac{P_s\,|h_{sr}|^2}{d_1^{±1}}+N_0}}\frac{h_{rd}}{\sqrt{d_2^{±2}}}n_r+n_d. \quad (4)$$

The instantaneous received SNR at the destination can be given by

$$¥_{e2e}=\frac{P_rP_s¥_1¥_2}{(P_r¥_2+P_s¥_1)N_0+N_0^2}=$$
$$=\frac{aP_s^2¥_1^2¥_2}{(aP_s¥_1¥_2+P_s¥_1)N_0+N_0^2}, \quad (5)$$

where $¥_1=\frac{|h_{sr}|^2}{d_1^{±1}}$, $¥_2=\frac{|h_{rd}|^2}{d_2^{±2}}$.

In high SNR region, it holds that

$$¥_{e2e}\sim\frac{aP_S¥_1¥_2}{(a¥_2+1)N_0}. \quad (6)$$

The probability density function (PDF) of RV $¥_1$ is [6]

$$f_{¥_1}(x)=\frac{(K+1)e^{-K}}{ª_1}e^{-\frac{(K+1)x}{ª_1}}I_0\left(2\sqrt{\frac{K(K+1)x}{ª_1}}\right), \quad (7)$$

where $ª_1=\mathbf{E}\left(|h_{sr}|^2\right)/d_1^{±1}$, K is the Rician K-factor defined as the ratio of the powers of the LOS component to the scattered components and $I_0(\bullet)$ is the *zero*-th order modified Bessel function of the first kind.

We can rewrite (7) as follows

$$f_{¥_1}(x)=p\sum_{l=0}^{\infty}\frac{(qK)^l}{(l!)^2}x^le^{-qx}, \quad (8)$$

where $p=\frac{(K+1)e^{-K}}{ª_1}, q=\frac{K+1}{ª_1}$, and $I_0(x)=\sum_{l=0}^{\infty}\frac{x^{2l}}{2^{2l}(l!)^2}$ [15].

The cumulative density function (CDF) of RV $¥_1$ can be constituted as in [9]

$$F_{¥_1}(¥)=\int_0^{¥}f_{¥_1}(x)dx=1-\frac{p}{q}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{K^lq^m}{l!m!}¥^me^{-q¥}. \quad (9)$$

The PDF and CDF of RV $¥_2$ are respectively given by: for PDF

$$f_{¥_2}(x)=ª_2e^{-ª_2x}, \quad (10)$$

and for CDF as

$$F_{¥_2}(x)=1-e^{-ª_2x}, \quad (11)$$

where $ª_2=d_2^{±2}/\mathbf{E}\left(|h_{rd}|^2\right)$.

III. PERFORMANCE ANALYSIS

A. Outage Probability (OP)

Outage probability is an important performance metric that is generally used to characterize a wireless communication system. It is defined as the probability that the instantaneous end-to-end SNR - $¥_{e2e}$, falls below the predetermined threshold $¥_0$, given by

$$P_{out}=F_{¥_{e2e}}(¥_0)=Pr\left(\frac{aP_s¥_1¥_2}{(a¥_2+1)N_0}<¥_0\right), \quad (12)$$

where that $F_{¥_{e2e}}(¥_0)$ is CDF of the instantaneous end-to-end SNR, $¥_0=2^R-1$, R is fixed transmission rate at the source.

We can derive the outage probability P_{out} as (16) (see more detail in the Appendix A).

B. Throughput (²)

At this point, we analyse throughput (²) at the destination node for delay-limited transmission mode. It is found out by evaluating OP at a fixed source transmission rate – R bits/s/Hz, in which $R=\log_2(1+¥_0)$. We observe that the source transmit information at the rate of R bit/s/Hz and the effective communication time from the source node to the destination node in the block time T is $(1-\sim)T/2$. Thence, throughput ² at the destination is defined as

$$² =(1-P_{out})R\frac{(1-\sim)T/2}{T}=\frac{(1-\sim)(1-P_{out})R}{2}. \quad (13)$$

C. Average Symbol Error Probability (ASEP)

ASEP, which is another prominent measure, is very useful for system designers to evaluate a wireless communication network. The ASEP of communication link over fading channels is given by

$$P_s(e)=\int_0^{\infty}µQ\left(\sqrt{¯¥}\right)f_{¥_{e2e}}(¥)d¥, \quad (14)$$

where $Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}e^{-t^2/2}dt$ is the Gaussian Q-function, µ and ¯ are constants which is specific for modulation type.

According to [6], we can further express (13) as follows

$$P_s(e)=\frac{µ}{\sqrt{2\pi}}\int_0^{\infty}F_{¥_{e2e}}\left(\frac{t^2}{¯}\right)e^{-t^2/2}dt=$$
$$=\frac{µ}{2\sqrt{2\pi}}\int_0^{\infty}F_{¥_{e2e}}\left(\frac{t}{¯}\right)e^{-t/2}t^{-1/2}dt. \quad (15)$$

By using the calculation result of (16), we obtain as (17) (see Appendix B).

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we provide simulation and analytical results for OP and ASEP to clarify the impact of parameters, such as energy harvesting time (~), energy harvesting efficiency (¦) and relay location (d_1) on these two quantities.

A. Verification of Analytical Results

In this subsection, the analytical results for OP and ASEP are evaluated and verified through simulations. Figure 2 plots OP and ASEP with respect to P_S and the applied modulation types are BPSK and QPSK, respectively. In general, we can see that the superior match between analytical and simulation results occurs in the high SNR or in large P_S region. In more clear explanation, when P_S holds low values, the analytical and simulation results does not match very well because we use approximated formulation of the received SNR at the destination (¥$_{e2e}$) as (6). In addition, Fig. 2 also indicates obviously that OP and ASEP decrease with the growth of P_S due to the increase level of ¥$_{e2e}$ and ASEP for BPSK modulation is lower than that of QPSK modulation.

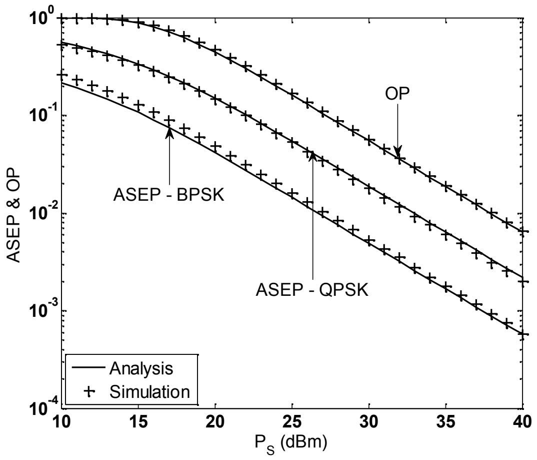

Fig. 2. OP and ASEP vs. transmit power P_S with ~ = 0.4, ¦ = 1, $d_1 = d_2 = 1$, $K = 3$, $R = 2$, ±$_1$ = 2, ±$_2$ = 3, $N_0 = 0.01$.

B. Effect of Energy Harvesting Time (~)

In Fig. 3 and Fig. 4, the impacts of ~ on OP, ASEP (Fig. 3) and throughput ² (Fig. 4) are shown. Figure 3 depicts that when ~ scales up, OP and ASEP go down. This can be explained by that there is more time for energy harvesting as ~ grows. Therefore, we may observe the smaller values of OP and ASEP at the destination node when ~ grows. For the throughput ² in Fig. 4, we can realize the existence of the specific value of ~ (we can let it be ~ * which is roughly equal to 0.21 in our considered system) which helps ² to get peak value. Throughput ² is directly proportional to ~ in the range from 0 to ~ *, however, it starts with decreasing from the ~ * value in the entire range. The reason is that there is less time for energy harvesting when ~ is smaller than ~ * value. Consequently, less energy is gathered which leads to higher OP can be obtained, and thence the smaller values of throughput are observed at the destination node. In the other words, for the values of ~ which is greater than ~ *, the more waste of time on energy harvesting is realized while less time is available for information transmission. Hence, lower throughput values are achieved at the destination node because of smaller value of (1 - ~)/2.

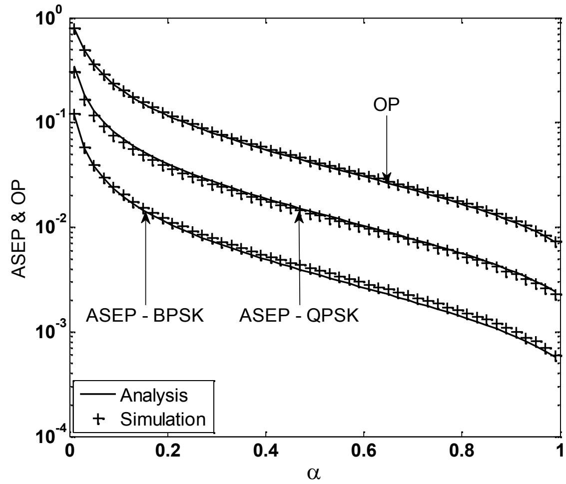

Fig. 3. OP and ASEP vs. energy harvesting time ~ with P_S = 1 W, ¦ = 1, $d_1 = d_2 = 1$, $K = 3$, $R = 2$, ±$_1$ = 2, ±$_2$ = 3, $N_0 = 0.01$.

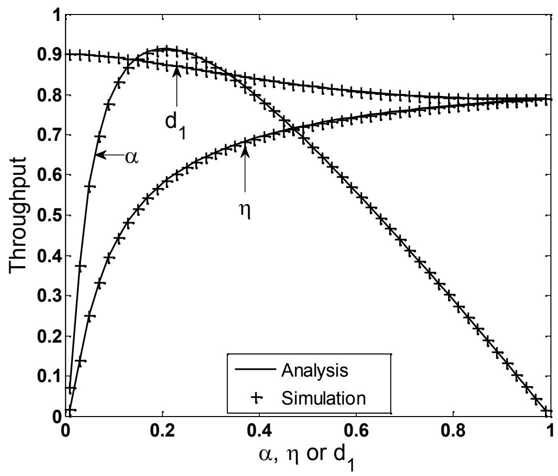

Fig. 4. Throughput ² vs. ~ , ¦ or d_1 with P_S = 1 W, $d_2 = 2 - d_1$, $K = 3$, $R = 3$, ±$_1$ = 2, ±$_2$ = 3, $N_0 = 0.01$.

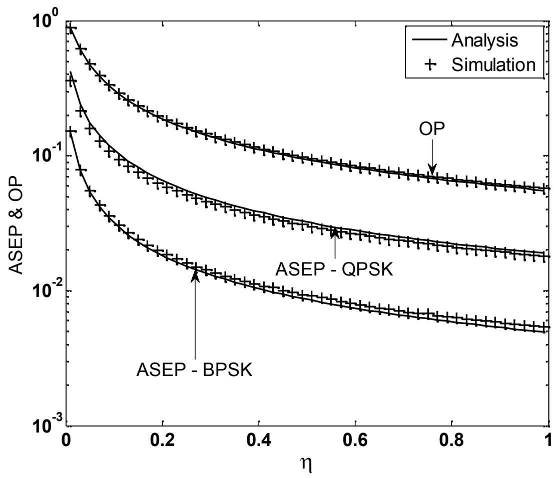

Fig. 5. OP and ASEP vs. energy harvesting efficiency ¦ with P_S = 1 W, ~ = 0.4, $d_1 = d_2 = 1$, K = 3, R = 2, ±$_1$ = 2, ±$_2$ = 3, N_0 = 0.01.

C. Effect of Energy Harvesting Efficiency (¦)

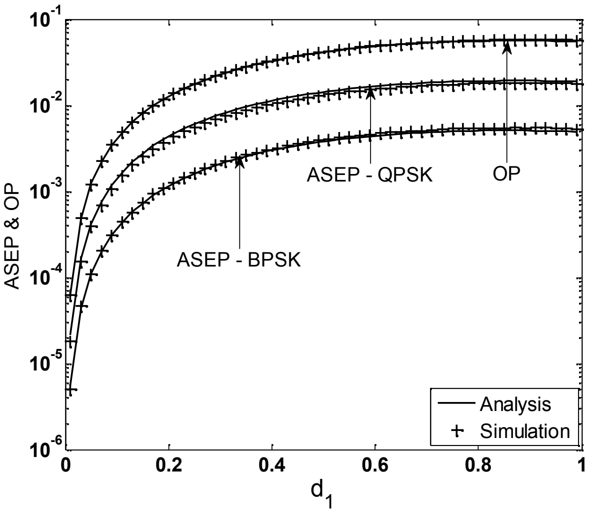

Fig. 6. OP and ASEP vs. the distance from source to relay d_1 with P_S = 1 W, ~ = 0.4, ¦ = 1, d_2 = 2 - d_1, K = 3, R = 2, $±_1$ = 2, $±_2$ = 3, N_0 = 0.01.

The effects of ¦ on OP, ASEP and throughput ² are shown in Fig. 4 (²) and Fig. 6 (OP and ASEP). Considering Fig. 5, OP and ASEP decrease with respect to the growth of ¦ . This can be explained that the higher ¦ is, the more energy is harvested. As a result, the lower values of OP and ASEP at the destination node are viewed. At the same time, we attain the higher value of ² when ¦ increases due to the degradation of OP. This result is shown in Fig. 4.

D. Effect of Relay Location (d_1)

The effects of Relay location (d_1) *on OP, ASEP and* ² are shown in Fig. 4 and Fig. 6. In Fig. 6, contrary to two aforementioned cases, d_1 makes OP and ASEP grow when it scales up. In fact, the higher values of $d_1^{±1}$ lead to the smaller values of energy are collected as well as the received signal strength (*y(t)*) at the relay node. Therefore, we observe that the achievable values of ² fall down as in Fig. 4 due to the reduction of received signal strength at the destination.

V. CONCLUSIONS

In this paper, we have derived the closed-form expressions of OP and ASEP. Based on the result of OP, we have examined throughput ² for delay-limited transmission mode. The considered system model comprises a power transfer and information source, an energy constrained relay and a destination over dissimilar fading environments. Specifically, the channels between the source to relay and the relay to destination are assumed to undergo Rician and Rayleigh fading, respectively. These analytical derivations have been validated by Monte-Carlo simulation. Furthermore, we have also distinctly evaluated the impact of system parameters such as energy harvesting time (~), energy harvesting efficiency (¦) and relay location (d_1) on studied quantities in our work.

APPENDIX A

Here we calculate (12) as (16). Note that, we have used the following relation in our calculation

$$(x+y)^m = \sum_{n=0}^{m} \binom{m}{n} x^{m-n} y^n,$$

$$t = \frac{1}{¥_2},$$

$$\int_0^\infty t^{¬-1} e^{-\frac{}{t}-«t}\, dt = 2\left(\frac{}{«}\right)^{¬/2} \mathcal{K}_¬\left(2\sqrt{\;«}\right),$$

where , « are positive real values and $\mathcal{K}_¬(.)$ is the modified Bessel function of the second kind and $¬^{th}$ order.

APPENDIX B

Here we employ two following equations (3.361.1) and (6.643.3) in [15] to yield (17)

$$\int_0^\infty \frac{e^{-qt}}{\sqrt{t}} dt = \sqrt{\frac{\pi}{q}},$$

$$\int_0^\infty t^{«-\frac{1}{2}} e^{-~t} \mathcal{K}_{2¬}\left(2\;\sqrt{t}\right) dt = \frac{~^{-«}}{2} \Gamma\left(« - ¬ + \frac{1}{2}\right)\Gamma \times$$

$$\times\left(« + ¬ + \frac{1}{2}\right) exp\left(\frac{2}{2~}\right) \mathcal{W}_{-«,¬}\left(\frac{2}{~}\right),$$

where $\mathcal{W}(.)$ is the Whittaker function.

$$P_{out} = F_{¥_{e2e}}(¥_0) = \int_0^\infty Pr\left[¥_1 < \frac{a¥_0¥_2 + ¥_0}{a¥_2 P_S / N_0} | ¥_2\right] f_{¥_2}(¥_2) d¥_2 =$$

$$= \int_0^\infty F_{¥_1}\left(\frac{a¥_0¥_2 + ¥_0}{a¥_2 P_S / N_0}\right) f_{¥_2}(¥_2) d¥_2 =$$

$$= 1 - \frac{p^{ª}{}_2}{q} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \binom{m}{n} \frac{K^l q^m}{l!m!a^n} \left(\frac{¥_0}{P_S / N_0}\right)^{m-n} e^{-\frac{q¥_0}{P_S/N_0}} \int_0^\infty t^{n-2} e^{-\frac{ª_2}{t} - \frac{q¥_0}{aP_S/N_0}t} dt =$$

$$= 1 - \frac{2p}{q} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l (ª_2)^{(n+1)/2}}{l!n!(m-n)!a^{(n+1)/2}} \left(\frac{q¥_0}{P_S / N_0}\right)^{m-(n-1)/2} e^{-\frac{q¥_0}{P_S/N_0}} \mathcal{K}_{n-1}\left(2\sqrt{\frac{ª_2 q¥_0}{aP_S / N_0}}\right). \quad (16)$$

$$P_s(e) = \frac{\mu}{2\sqrt{2\pi}} \int_0^{\infty} F_{¥_{e2e}}\left(\frac{t}{-}\right) e^{-t/2} t^{-1/2} dt =$$

$$= \frac{\mu}{2\sqrt{2\pi}} \int_0^{\infty} \left[1 - \frac{2p}{q} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l (\text{ª}_2)^{(n+1)/2}}{l!n!(m-n)!a^{(n+1)/2}} \left(\frac{qt}{\bar{P}_S / N_0}\right)^{m-(n-1)/2} e^{-\frac{qt}{\bar{P}_S/N_0}} \mathcal{K}_{n-1}\left(2\sqrt{\frac{\text{ª}_2 qt}{a \bar{P}_S / N_0}}\right) \right] e^{-t/2} t^{-1/2} dt =$$

$$= \frac{\mu}{2\sqrt{2\pi}} \int_0^{\infty} e^{-t/2} t^{-1/2} dt -$$

$$- \frac{\mu p}{q\sqrt{2\pi}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l (\text{ª}_2)^{(n+1)/2}}{l!n!(m-n)!a^{(n+1)/2}} \left(\frac{q}{\bar{P}_S / N_0}\right)^{m-(n-1)/2} \int_0^{\infty} t^{m-n/2} e^{-\left(\frac{q}{\bar{P}_S/N_0}+\frac{1}{2}\right)t} \mathcal{K}_{n-1}\left(2\sqrt{\frac{\text{ª}_2 qt}{a \bar{P}_S / N_0}}\right) dt =$$

$$= \frac{\mu}{2} - \frac{\mu p}{q 2\sqrt{2\pi}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \sum_{n=0}^{m} \frac{K^l (\text{ª}_2)^{n/2}}{l!n!(m-n)!a^{n/2}} \left(\frac{q}{\bar{P}_S / N_0}\right)^{m-n/2} \left(\frac{q}{\bar{P}_S / N_0} + \frac{1}{2}\right)^{-m+(n-1)/2} \times$$

$$\times \Gamma\left(m-n+\frac{3}{2}\right) \Gamma\left(m+\frac{1}{2}\right) exp\left(\frac{\text{ª}_2 q}{a(2q+\bar{P}_S / N_0)}\right) \mathcal{W}_{-m+(n-1)/2,(n-1)/2}\left(\frac{2\text{ª}_2 q}{a(2q+\bar{P}_S / N_0)}\right). \quad (17)$$

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