Performance Analysis of Wireless Powered UAV Relaying Systems over κ-μ Fading Channels

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***Abstract*—In this paper, the performance of wireless powered unmanned aerial vehicle (UAV) relaying systems employing the decode-and-forward (DF) or the amplify-and-forward (AF) protocols is investigated. Both source and destination nodes are equipped with multiple antennas. The considered system operates in the presence of κ-μ fading. Analytical expressions for the outage probability (OP), the symbol error rate (SER), and the average capacity (AC) are derived by employing Mellin-transform techniques. Based on the derived formulae, the impact of the number of antennas and the fading parameters on system performance are further investigated and useful system performance optimization suggestions are proposed. The correctness of the proposed analysis is validated through Monte Carlo simulations.**

***Index Terms*—Wireless power transfer, unmanned aerial vehicles (UAV), Mellin transforms, κ-μ fading channels.**

I. Introduction

Unmanned aerial vehicle (UAV) aided relaying communication can provide communication connectivity for separated users without direct communication links [1]–[4]. However, the greatest obstacle to the application of UAV-aided relaying networks is energy-constrained issues (e.g., recharging and replacement of batteries) [5]. Motivated by the concept of energy harvesting (EH), the so-called simultaneous wireless information and power transfer (SWIPT) networks are considered as a promising solution to overcome the aforementioned problems [6], [7]. The performance of EH systems has been addressed in several past research works. For example, in [8], the performance of a dual-hop relaying system over log-normal fading channels with three kinds of EH protocols, namely, time-switching relaying (TSR), power-splitting relaying (PSR), and ideal relaying receiver (IRR) has been evaluated. The throughput performance with TSR and PSR protocols in a decode-and-forward (DF) relaying system over non-selective Rayleigh fading channels was investigated in [9]. Moreover, physical layer security of amplify-and-forward (AF) relaying EH-based networks with multi-antennas and operating over Rayleigh fading channels has been considered in [10]. However, the analysis presented in most of previous works is valid only for the well-known small-scale fading channels (e.g., Rayleigh, Rician, and Nakagami-m), which are not able to accurately model random fluctuations in many practical scenarios due to their limited versatility [11]–[15]. The κ-μ distribution proposed in [16] is a generalized fading model which provides a better fit to line-of-sight empirical measurements of the UAV propagation phenomena. Moreover, it includes the Rayleigh, Rician, and Nakagami-m distribution as special cases [16]. Because of its versatility, the κ-μ distribution has attracted the interest of the research community in the context of performance evaluation of digital communications over fading channels. For example, in [17], the effective throughput of multiple-input-single-output systems over κ-μ fading channels has been studied. Analytical expressions for the high-order capacity statistics of spectrum aggregation systems have been derived in [18]. The error exponent of multiple-input-multiple-output systems operating over κ-μ fading channels was derived in [19]. However, the performance of UAV communications systems operating over κ-μ fading channels is not available in the opening technical literature and thus is the subject of our current contribution.

Motivated by the above considerations, this paper investigates the performance of a wireless powered UAV-aided system with both AF and DF relay, which is operating over the κ-μ fading channels. Because of the high hardware complexity of the PSR protocol and the unattainability of the IRR protocol, hereafter only the performance of the TSR protocol is considered. For the system under consideration, exact analytical expressions for the outage probability (OP), the symbol error rate (SER) and the average capacity (AC) are derived. Based on these results, insightful engineering guidelines for system optimization are further provided.

II. System Model

Let us consider a wireless powered UAV relaying system consisting of a source node $\mathbb{S}$, a destination node $\mathbb{D}$ and a relay node $\mathbb{R}$, i.e., an UAV. Nodes $\mathbb{S}$ and $\mathbb{D}$ are equipped with N_1 and N_2 antennas, respectively, whereas the UAV is equipped with a single antenna due to the energy and weight constraints. Information is transmitted from $\mathbb{S}$ to $\mathbb{D}$ with power P_s via

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node $\mathbb{R}$. Hereafter, h_1 and h_2 denote the quasi-static block-fading channel gains of $\mathbb{S}\rightarrow\mathbb{R}$ and $\mathbb{R}\rightarrow\mathbb{D}$ links and d_1 and d_2 their corresponding distances, respectively. Assuming long link distances, no direct link between $\mathbb{S}$ and $\mathbb{D}$ exists, and the energy that the UAV uses to forward information to $\mathbb{D}$ is obtained entirely from $\mathbb{S}$ by employing EH techniques.

A. Time-Switching Relaying Protocol

Hereafter, it is assumed that the considered system employs the simple TSR protocol. Let T denotes the whole time frame required for communication, which is divided into three slots determined by the time factor τ, $(0 \leq \tau \leq 1)$. During the first slot, τT, and the second slot, $(1-\tau)\,T/2$, $\mathbb{S}$ broadcasts a RF signal to the UAV by employing maximum-ratio transmission. The UAV harvests energy and receives information from the RF signal during the first and the second slot, respectively. In the remaining duration of the time frame, the UAV processes and forwards the information to $\mathbb{D}$ by employing the AF or the DF protocols. Finally, node $\mathbb{D}$ combines the received signal using maximum-ratio combining.

At medium and high SNR regimes, the end-to-end instantaneous SNR at $\mathbb{S}$ can be well approximated as [20], [21]

$$\gamma_t = \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}, \tag{1}$$

where

$$\gamma_1 = \frac{P_s h_1^2}{d_1^m} = \frac{h_1^2}{\alpha}, \tag{2}$$

$$\gamma_2 = \frac{2\eta\tau P_s h_1^2 h_2^2}{(1-\tau)\,d_1^m d_2^m} = \frac{h_1^2 h_2^2}{\beta}, \tag{3}$$

are the instantaneous SNRs of the first and second hop [8, Eq. (8-9)], respectively, m is the path loss exponent and η is the efficiency factor mainly determined by the receiver circuitry at the UAV relay. The overall noise variances at $\mathbb{R}$ and $\mathbb{D}$ are normalized such that $\sigma_1^2 = \sigma_2^2 = 1$.

B. κ-μ fading channel

The κ-μ distribution is a generalized fading model which can well model small-scale variations of the fading signal when dominant components and multiple clusters of multipath waves are present [16]. Under the assumption of κ-μ fading, h_ℓ^2, $\forall\ell \in \{1,2\}$, are independent and identically distributed (i.i.d.) non-central chi-squared random variable (RVs). The probability distribution function (pdf) and the complementary cumulative distribution function (ccdf) of h_ℓ^2 are given as [16, Eq. (10), Eq. (3)]

$$f_{h_\ell^2}(\omega) = \frac{N_\ell\mu_\ell\psi_\ell^{\frac{N_\ell\mu_\ell+1}{2}}\omega_\ell^{\frac{N_\ell\mu_\ell-1}{2}}}{e^{N_\ell\mu_\ell\kappa_\ell}\kappa_\ell^{\frac{N_\ell\mu_\ell-1}{2}}} e^{-\mu_\ell\psi_\ell\omega} \times I_{N_\ell\mu_\ell-1}\left(2\mu_\ell\sqrt{N_\ell\kappa_\ell\psi_\ell\omega_\ell}\right), \tag{4}$$

$$\overline{F_{h_\ell^2}}(\omega) = Q_{N_\ell\mu_\ell}\left(\sqrt{2N_\ell\mu_\ell\kappa_\ell}, \sqrt{2\mu_\ell\psi_\ell\omega_\ell}\right). \tag{5}$$

where $\psi_\ell = \frac{1+\kappa_\ell}{\Omega_\ell}$ with Ω_ℓ being the average powers, κ_ℓ is the ratio of total power between the dominant components and the scatter components, and μ_ℓ is related to the number of multipath clusters. Finally, $I_\nu(\cdot)$ is the modified Bessel function of the first kind with order ν [22, Eq. (8.445)], and $Q_\nu(\cdot)$ is the Marcum Q-function [23].

TABLE I
REQUIRED TERMS AND TRUNCATION ERROR FOR DIFFERENT COMBINATIONS OF κ-μ PARAMETERS N_ℓ, κ_ℓ, AND μ_ℓ $(\Omega = 10)$.

Fading Parameters	$\varepsilon(L_\ell)$	L_ℓ
N_ℓ=1, κ_ℓ=2, μ_ℓ=2	1.69433×10^{-5}	12
N_ℓ=4, κ_ℓ=2, μ_ℓ=2	1.91925×10^{-5}	36
N_ℓ=4, κ_ℓ=3.5, μ_ℓ=2	1.65227×10^{-5}	47
N_ℓ=4, κ_ℓ=3.5, μ_ℓ=3	1.35327×10^{-5}	66

By employing [22, Eq. (8.445)] and [22, Eq. (3.351.2)], an infinite series representation of $f_{h_\ell^2}(\omega)$ and $\overline{F_{h_\ell^2}}(\omega)$ can be deduced as

$$f_{h_\ell^2}(\omega) = \sum_{n=0}^{\infty} \frac{N_\ell^n \mu_\ell^{N_\ell\mu_\ell+2n}\psi_\ell^{N_\ell\mu_\ell+n}\kappa_\ell^n}{n! e^{N_\ell\mu_\ell\kappa_\ell}\Gamma(N_\ell\mu_\ell+n)} \times \omega^{N_\ell\mu_\ell+n-1}e^{-\mu_\ell\psi_\ell\omega}, \tag{6}$$

$$\overline{F_{h_\ell^2}}(\omega) = \sum_{i=0}^{\infty}\sum_{j=0}^{N_\ell\mu_\ell+i-1} \frac{N_\ell^i\mu_\ell^{i+j}\kappa_\ell^i\psi_\ell^j\omega^j}{i!j!e^{N_\ell\mu_\ell\kappa_\ell+\mu_\ell\psi_\ell\omega}}, \tag{7}$$

where $\Gamma(\cdot)$ is the Gamma Function [22, Eq. (8.310.1)] and μ_ℓ is a positive integer. Note that (6) and (7) converge rapidly requiring rather few terms for achieving a given accuracy, depending on the number of antennas N_ℓ and the fading parameters κ_ℓ and μ_ℓ. The validity of the convergence is numerically investigated in Table I.

C. Truncation Error

By truncating (6) to $L_\ell+1$ terms and following similar steps in [24], one can obtain

$$\hat{f}_{h_\ell^2}(\omega) = \sum_{n=0}^{L_\ell} \frac{N_\ell^n \mu_\ell^{N_\ell\mu_\ell+2n}\psi_\ell^{N_\ell\mu_\ell+n}\kappa_\ell^n}{n! e^{N_\ell\mu_\ell\kappa_\ell}\Gamma(N_\ell\mu_\ell+n)} \times \omega^{N_\ell\mu_\ell+n-1}e^{-\mu_\ell\psi_\ell\omega}. \tag{8}$$

The truncation error is given as

$$\varepsilon(L_\ell) \triangleq \left|\hat{f}_{\kappa-\mu}(\omega) - f_{\kappa-\mu}(\omega)\right|. \tag{9}$$

Table I shows the truncation error assuming different values of N_ℓ, κ_ℓ, and μ_ℓ and Ω of 10. It is obvious that the maximum value of L_ℓ for achieving sufficient accuracy is only 66 in all considered cases.

III. PERFORMANCE ANALYSIS

A. Outage Probability Analysis

An outage event occurs when the instantaneous capacity, $C(\gamma)$, falls bellow a predetermined threshold (C_{th}). Since information transmission only takes place during the second and third slots, respectively, $C(\gamma)$ can be written as

$$C(\gamma) = \frac{1-\tau}{2}\log_2(1+\gamma), \tag{10}$$

where γ denotes the instantaneous SNR.

1) OP Analysis of DF Systems: The OP of DF relaying systems, is defined as the probability that either one of the two-hop links is in outage. Mathematically speaking, OP can be expressed as

$$P_{out}^{DF}(C_{th}) = \Pr\{\min\{C(\gamma_1), C(\gamma_2)\} < C_{th}\}. \tag{11}$$

Using (2), (3) and (10) and setting $h_1^2 = X$ and $h_2^2 = Y$, (11) can be rewritten as

$$\begin{aligned} P_{out}^{DF}(C_{th}) &= 1 - \Pr\left\{X \geq \alpha\lambda, Y \geq \frac{\beta\lambda}{X}\right\} \\ &= 1 - \int_{\alpha\lambda}^{\infty} f_X(x)\overline{F_Y}\left(\frac{\beta\lambda}{x}\right)\mathrm{d}x, \end{aligned} \tag{12}$$

where $\lambda \triangleq 2^{\frac{2C_{th}}{1-\tau}} - 1$. Substituting (6) and (7) into (12), $P_{out}^{DF}(C_{th})$ can be expressed as

$$\begin{aligned} P_{out}^{DF}(C_{th}) = 1 - &\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_2\mu_2+j-1} \frac{\Xi^i\Upsilon^{N_1\mu_1+i}\Psi^j\Theta^k}{i!j!k!e^{\Xi+\Psi}} \\ &\times \frac{\beta^k\lambda^k}{\Gamma(N_1\mu_1+i)} \underbrace{\int_{\alpha\lambda}^{\infty} x^{N_1\mu_1+i-k-1}e^{-\Upsilon x - \frac{\Theta\beta\lambda}{x}}dx}_{\mathcal{I}_1}, \end{aligned} \tag{13}$$

where $\Upsilon \triangleq \mu_1\psi_1$, $\Xi \triangleq N_1\mu_1\kappa_1$, $\Theta \triangleq \mu_2\psi_2$, and $\Psi \triangleq N_2\mu_2\kappa_2$. In order to obtain an exact expression for $P_{out}^{DF}(C_{th})$, the integral $\mathcal{I}_1$ given in (13) needs to be computed. Specifically, the following Lemma holds.

Lemma. *$\mathcal{I}_1$ can be evaluated in closed form as*

$$\begin{aligned} \mathcal{I}_1 &= (\alpha\lambda)^{N_1\mu_1+i-k} \\ &\times G_{1,1;1,0;0,1}^{1,0;0,1;1,0}\left(\begin{matrix} k-i-N_1\mu_1 \\ k-i-N_1\mu_1+1 \end{matrix}\middle| \begin{matrix} 1 \\ - \end{matrix}\middle| \begin{matrix} - \\ 0 \end{matrix}\middle| \frac{1}{\alpha\lambda\Upsilon}, \frac{\Theta\beta}{\alpha}\right), \end{aligned} \tag{14}$$

where $G_{\cdot,\cdot;\cdot,\cdot;\cdot,\cdot}^{\cdot,\cdot;\cdot,\cdot;\cdot,\cdot}\left(\begin{matrix} \cdot \\ \cdot \end{matrix}\middle| \begin{matrix} \cdot \\ \cdot \end{matrix}\middle| \begin{matrix} \cdot \\ \cdot \end{matrix}\middle| \cdot,\cdot\right)$ denotes the extended generalized bivariate Meijer's G-function (EGBMGF) [25].

Proof: Please see Appendix. ■

Substituting (14) into (13), the analytical OP of DF relaying system can be obtained as (15) at the bottom of this page.

2) OP Analysis of AF Systems: The OP of AF relaying systems is defined as the probability that the end-to-end link is in outage, which can be expressed as

$$P_{out}^{AF}(C_{th}) = \Pr\{C(\gamma_t) < C_{th}\}. \tag{16}$$

Using (1) and (10), (16) can be rewritten as

$$\begin{aligned} P_{out}^{AF}(C_{th}) &= 1 - \Pr\left\{X \geq \alpha\lambda + \frac{\beta\lambda}{Y}\right\} \\ &= 1 - \int_0^{\infty} f_Y(y)\overline{F_X}\left(\alpha\lambda + \frac{\beta\lambda}{y}\right)\mathrm{d}y. \end{aligned} \tag{17}$$

Substituting (6) and (7) into (17), and employing [22, Eq. (3.471.9)], the analytical OP of AF relaying system can be deduced as (18) at the bottom of this page, where $K_\nu(\cdot)$ is the νth order modified Bessel function of second kind [22].

B. Symbol Error Rate Analysis

The SER of various modulations is given as [26, Eq. (31)]

$$P_{SER} = \frac{a}{2}\sqrt{\frac{b}{\pi}}\int_0^{\infty}\frac{e^{-b\gamma}}{\sqrt{\gamma}}F(\gamma)\,\mathrm{d}\gamma, \tag{19}$$

where $F(\gamma)$ is the cdf of the instantaneous SNR, γ. Note that $F(\gamma)$ can be directly yielded from $P_{out}(C_{th})$ by substituting λ with γ, i.e.,

$$F(\gamma) = P_{out}\left(\frac{1-\tau}{2}\log_2(1+\gamma)\right). \tag{20}$$

Moreover, a and b depend on the specific modulation format, e.g., for binary phase shift keying (BPSK) ($a = b = 1$), for BFSK with orthogonal signalling ($a = 1, b = 0.5$), and for M-ary pulse amplitude modulation ($a = \frac{2(M-1)}{M}, b = \frac{3}{M^2-1}$) [27], [28].

1) SER Analysis in DF Systems: Using (12), (33), (19), (20) and employing [22, Eq. (3.361.2)] and [22, Eq. (3.351.3)], an analytical expression for the SER of DF systems can be deduced as (21) at the bottom of next page.

2) SER Analysis in AF Systems: Substituting (18) into (19) with $\gamma = \lambda$, and employing [22, Eq. (6.631.3)], an analytical expression for the SER of AF systems can be deduced as (22) at the bottom of next page, where $W_{\lambda,\mu}(\cdot)$ is the Whittaker Function [22, Eq. (9.220.2)].

$$P_{out}^{DF}(C_{th}) = 1 - \sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_2\mu_2+j-1}\frac{\Xi^i\Upsilon^{N_1\mu_1+i}\Psi^j\Theta^k\alpha^{N_1\mu_1+i-k}\beta^k\lambda^{N_1\mu_1+i}}{i!j!k!e^{\Xi+\Psi}\Gamma(N_1\mu_1+i)} G_{1,1;1,0;0,1}^{1,0;0,1;1,0}\left(\begin{matrix} k-i-N_1\mu_1 \\ k-i-N_1\mu_1+1 \end{matrix}\middle| \begin{matrix} 1 \\ - \end{matrix}\middle| \begin{matrix} - \\ 0 \end{matrix}\middle| \frac{1}{\alpha\lambda\Upsilon}, \frac{\Theta\beta}{\alpha}\right). \tag{15}$$

$$P_{out}^{AF}(C_{th}) = 1 - 2\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_1\mu_1+j-1}\sum_{l=0}^{k}\frac{\Psi^i\Theta^{\frac{N_2\mu_2+i+k-l}{2}}\Xi^j\Upsilon^{\frac{N_2\mu_2+i+k+l}{2}}\alpha^l\beta^{\frac{N_2\mu_2+i+k-l}{2}}\lambda^{\frac{N_2\mu_2+i+k+l}{2}}}{i!j!l!(k-l)!e^{\Psi+\Xi+\Upsilon\alpha\lambda}\Gamma(N_2\mu_2+i)} K_{N_2\mu_2+i-k+l}\left(2\sqrt{\Upsilon\beta\lambda\Theta}\right), \tag{18}$$

C. Average Capacity Analysis

The average capacity is defined as the expectation of the instantaneous mutual information, i.e., $\overline{C} = \mathbb{E}\left\{\frac{1-\tau}{2}\log_2\left(1+\gamma\right)\right\}$, which can also be expressed in terms of $F\left(\gamma\right)$ as [29, Eq. (24)]

$$\overline{C} = \frac{1-\tau}{2\ln 2}\int_0^\infty \frac{1-F\left(\gamma\right)}{1+\gamma}\mathrm{d}\gamma. \tag{23}$$

1) AC Analysis in DF Systems: Using (12), (33), (23), (20), and employing [22, Eq. (3.194.3)] and [22, Eq. (8.384.1)], the AC of DF systems is given by (24) at the bottom of next page.

2) AC Analysis in AF Systems: Substituting (18) into (23) with $\gamma = \lambda$, the AC of AF systems can be expressed as

$$\begin{aligned}\overline{C^{AF}} &= \frac{1-\tau}{\ln 2}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_1\mu_1+j-1}\sum_{l=0}^{k}\frac{\Psi^i\Theta^{\frac{N_2\mu_2+i+k-l}{2}}\Xi^j}{i!j!l!\left(k-l\right)!}\\ &\times\frac{\Upsilon^{\frac{N_2\mu_2+i+k+l}{2}}\alpha^l\beta^{\frac{N_2\mu_2+i+k-l}{2}}}{e^{\Psi+\Xi}\Gamma\left(N_2\mu_2+i\right)}\\ &\times\underbrace{\int_0^\infty\underbrace{\frac{\gamma^{\frac{N_2\mu_2+i+k+l}{2}}}{1+\gamma}}_{\mathcal{F}_1}\underbrace{e^{-\Upsilon\alpha\gamma}}_{\mathcal{F}_2}\underbrace{K_{N_2\mu_2+i-k+l}\left(2\sqrt{\Upsilon\beta\Theta\gamma}\right)}_{\mathcal{F}_3}\mathrm{d}\gamma}_{\mathcal{I}_2}.\end{aligned} \tag{25}$$

Employing [30, Eq. (8.4.3.1)], [30, Eq. (8.4.23.1)], and [22, Eq. (9.31.5)], $\mathcal{F}_1$, $\mathcal{F}_2$, and $\mathcal{F}_3$ are respectively expressed as

$$\mathcal{F}_1 = G_{11}^{11}\left(x\left|\begin{array}{c}\frac{N_2\mu_2+i+k+l}{2}\\ \frac{N_2\mu_2+i+k+l}{2}\end{array}\right.\right), \tag{26}$$

$$\mathcal{F}_2 = G_{01}^{10}\left(\Upsilon\alpha\gamma\left|\begin{array}{c}-\\ 0\end{array}\right.\right), \tag{27}$$

$$\mathcal{F}_3 = \frac{1}{2}G_{02}^{20}\left(\Upsilon\beta\Theta\gamma\left|\begin{array}{c}-\\ \frac{N_2\mu_2+i-k+l}{2},-\frac{N_2\mu_2+i-k+l}{2}\end{array}\right.\right), \tag{28}$$

where $G_{p,q}^{m,n}\left(x\left|\begin{array}{c}a_1,\cdots,a_p\\ b_1,\cdots,b_q\end{array}\right.\right)$ is the Meijer's G-function (MGF) [22, Eq. (9.301)]. Substituting (26), (27) and (28) into (25), the integral $\mathcal{I}_2$ with integrand being the product of three MGFs needs to be solved. By employing [31, Eq. (07.34.22.0007.01)], $\overline{C^{AF}}$ can be obtained in closed form as (29) at the bottom of next page.

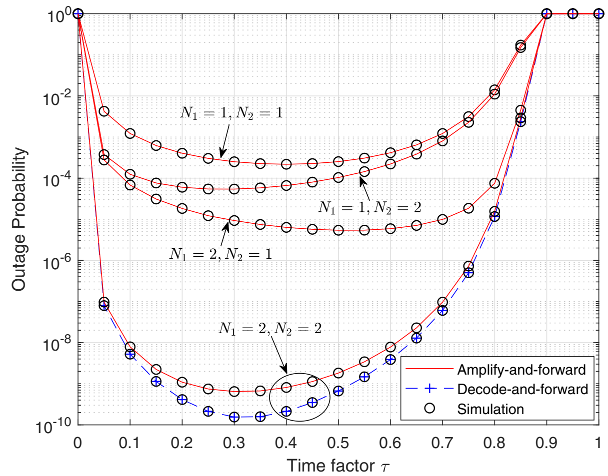

Fig. 1. OP versus τ with different number of antennas N_1, N_2, $\mu_1 = \mu_2 = 2$, and $\kappa_1 = \kappa_2 = 2$.

IV. Numerical Results

Using the expressions proposed in Section III, various performance evaluation results will be presented herein. Numerically results are obtained by truncating the infinite series representations so that the achievable truncation error, ε, is of the order of 10^{-5}. Unless specified otherwise, the following default parameters are used: $\Omega_1 = \Omega_2 = 10$ dB, $\eta = 1$, $m = 2$, $d_1 = d_2 = 3$ km, $P_s = 23$ dBW, and $C_{th} = 0.5$ bit/s/Hz.

Fig. 1 depicts the OP versus time factor τ for various antenna configurations. As it can be observed, OP significantly decreases as the number of antennas increases, due to the increase of the diversity order. Meanwhile, in the case of $N_1 = N_2 = 4$, it is clear that DF relaying offers better performance comparing to AF relaying. The reason is mainly that AF relaying amplifies both received signal and receiver noise at relay, yet DF relaying eliminates receiver noise when

$$\begin{aligned}P_{SER}^{DF} &= \frac{a}{2}-\frac{a}{2}\sqrt{\frac{b}{\pi}}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_2\mu_2+j-1}\frac{\Xi^i\Upsilon^{N_1\mu_1+i}\Psi^j\Theta^k\alpha^{N_1\mu_1+i-k}\beta^k}{i!j!k!e^{\Xi+\Psi}b^{N_1\mu_1+i+0.5}\Gamma\left(N_1\mu_1+i\right)}\\ &\times G_{1,1;1,1;0,1}^{1,0;1,1;1,0}\left(\begin{array}{c}k-i-N_1\mu_1\\ k-i-N_1\mu_1+1\end{array}\left|\begin{array}{c}1\\ N_1\mu_1+i+0.5\end{array}\right|\begin{array}{c}-\\ 0\end{array}\left|\frac{b}{\alpha\Upsilon},\frac{\Theta\beta}{\alpha}\right.\right).\end{aligned} \tag{21}$$

$$\begin{aligned}P_{SER}^{AF} &= \frac{a}{2}-\frac{a}{2}\sqrt{\frac{b}{\pi}}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_1\mu_1+j-1}\sum_{l=0}^{k}\frac{\Psi^i\Theta^{\frac{N_2\mu_2+i+k-l-1}{2}}\Xi^j\Upsilon^{\frac{N_2\mu_2+i+k+l-1}{2}}\alpha^l\beta^{\frac{N_2\mu_2+i+k-l-1}{2}}}{i!j!l!\left(k-l\right)!e^{\Psi+\Xi-\frac{\Upsilon\beta\Theta}{2(b+\Upsilon\alpha)}}\left(b+\Upsilon\alpha\right)^{\frac{N_2\mu_2+i+k+l}{2}}}\\ &\times\frac{\Gamma\left(0.5+N_2\mu_2+i+l\right)\Gamma\left(0.5+k\right)}{\Gamma\left(N_2\mu_2+i\right)}W_{-\frac{N_2\mu_2+i+k+l}{2},\frac{N_2\mu_2+i-k+l}{2}}\left(\frac{\Upsilon\beta\Theta}{b+\Upsilon\alpha}\right),\end{aligned} \tag{22}$$

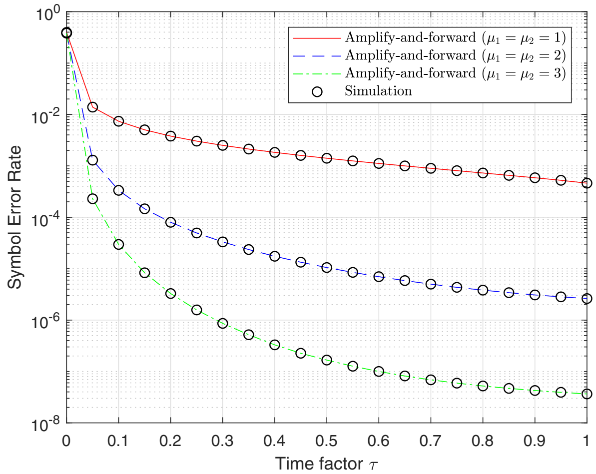

Fig. 2. SER versus τ with different fading parameters μ, $N_1 = N_2 = 1$, and $\kappa_1 = \kappa_2 = 2$.

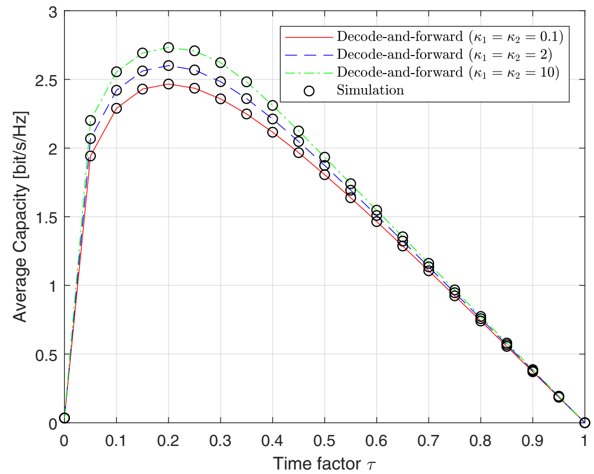

Fig. 3. Average capacity versus τ with different fading parameters κ, $N_1 = N_2 = 1$ and $\mu_1 = \mu_2 = 2$

received signal is decoded. It is worthwhile pointing out that the case of $N_1 = 2, N_2 = 1$ exhibits lower OP than the one of $N_1 = 1, N_2 = 2$, which indicates that better performance can be achieved by increasing the number of antennas at node $\mathbb{S}$ rather than that at node $\mathbb{D}$. Moreover, significant deteriorations in OP can be observed when τ approaches either 0 or 1 because of the fact that the energy harvested turns either too small or needlessly too large, which could bring about no time left for data transmission. Therefore, the optimization of τ is of great importance to improve the system performance.

Fig. 2 depicts the SER of AF systems with BPSK as a function of τ assuming different values of μ. Since the cdf $F(\gamma)$ is a monotonically decreasing function with respect to τ, SER is decreases as τ increases. Furthermore, it can be observed that SER also decreases as the fading parameter μ increases. Compared with Fig. 1, it is noted that the diversity order of considered system also depends on μ_ℓ as well as on N_ℓ. Specifically, the diversity order equals to $\min(N_1\mu_1, N_2\mu_2)$.

Fig. 3 illustrates the impact of τ on the AC of DF systems assuming different values of κ. Considerable deteriorations can be observed as τ approaches two extremes, i.e., 0 or 1, for the same reason as pointed out in the inspection of Fig. 1. Compared to the results depicted in Fig. 2, the performance of the considered system relies less on κ or on μ.

V. Conclusions

In this paper, the performance of wireless powered UAV-aided dual-hop relaying systems over κ-μ fading channels is investigated. Analytical expressions for important performance metrics, namely the OP, SER, and AC are derived. Numerical results revealed that DF relaying offers better performance compared to that of the AF relaying when the processing energy cost at the UAV is negligible. It has also been shown that the performance of the considered dual-hop system depends more on the first hop channel state than the one of the second hop. Besides, the fading parameter μ affects system performance more than κ. Moreover, due to the correlation between the two hops of channel, the system performance could be further improved by optimizing the time factor τ.

$$\overline{C^{DF}} = \frac{1-\tau}{2\ln 2}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_2\mu_2+j-1}\frac{\Xi^i \Upsilon^{N_1\mu_1+i}\Psi^j\Theta^k\alpha^{N_1\mu_1+i-k}\beta^k}{i!j!k!e^{\Xi+\Psi}\Gamma(N_1\mu_1+i)} \times G_{1,1;2,1;0,1}^{1,0;1,2;1,0}\left(\begin{array}{c} k-i-N_1\mu_1 \\ k-i-N_1\mu_1+1 \end{array}\middle| \begin{array}{c} 1, 1+N_1\mu_1+i \\ 1+N_1\mu_1+i \end{array}\middle| \begin{array}{c} - \\ 0 \end{array}\middle| \frac{1}{\alpha\Upsilon}, \frac{\Theta\beta}{\alpha}\right). \tag{24}$$

$$\overline{C^{AF}} = \frac{1-\tau}{2\ln 2}\sum_{i=0}^{\infty}\sum_{j=0}^{\infty}\sum_{k=0}^{N_1\mu_1+j-1}\sum_{l=0}^{k}\frac{\Psi^i\Theta^{\frac{N_2\mu_2+i+k-l}{2}}\Xi^j\Upsilon^{\frac{N_2\mu_2+i+k+l}{2}}\alpha^l\beta^{\frac{N_2\mu_2+i+k-l}{2}}}{i!j!l!(k-l)!e^{\Psi+\Xi}\Gamma(N_2\mu_2+i)} \times G_{11;01;02}^{11;10;20}\left(\begin{array}{c} -\frac{N_2\mu_2+i+k+l}{2} \\ -\frac{N_2\mu_2+i+k+l}{2} \end{array}\middle| \begin{array}{c} - \\ 0 \end{array}\middle| \begin{array}{c} - \\ \frac{N_2\mu_2+i-k+l}{2}, -\frac{N_2\mu_2+i-k+l}{2} \end{array}\middle| \Upsilon\alpha, \Upsilon\Theta\beta\right). \tag{29}$$

Appendix

Employing [30, Eq. (8.4.3.1)] and [30, Eq. (8.4.3.2)], the exponentials $e^{-\Upsilon x}$ and $e^{-\frac{\Theta\beta\lambda}{x}}$ in $\mathcal{I}_1$ can be expressed as inverse Mellin transforms as

$$e^{-\Upsilon x} = \frac{1}{2\pi\imath}\int_{\mathcal{C}_1} \Gamma\left(r\right)\Upsilon^{-r}x^{-r}\mathrm{d}r, \tag{30}$$

$$e^{-\frac{\Theta}{x}} = \frac{1}{2\pi\imath}\int_{\mathcal{C}_2} \Gamma\left(-s\right)\left(\frac{1}{\Theta\beta\lambda}\right)^{-s}x^{-s}\mathrm{d}s, \tag{31}$$

where $\mathcal{C}_1$ and $\mathcal{C}_2$ are the Mellin-Barnes contours satisfying $\mathcal{C}_1 : \{\delta_1 + \imath\xi_1, -\infty < \xi_1 < \infty, \delta_1 > 0\}$ and $\mathcal{C}_2 : \{\delta_2 + \imath\xi_2, -\infty < \xi_2 < \infty, \delta_2 < 0\}$. Using (30) and (31), and changing the order of integration, $\mathcal{I}_1$ can be expressed as

$$\begin{aligned}\mathcal{I}_1 = &\frac{1}{\left(2\pi\imath\right)^2}\int_{\mathcal{C}_1}\int_{\mathcal{C}_2}\left[\int_{\alpha\lambda}^{\infty} x^{N_1\mu_1+i-k-s-r-1}dx\right] \\ &\times\Gamma\left(-s\right)\Gamma\left(r\right)\left(\Theta\beta\lambda\right)^{s}\Upsilon^{-r}dsdr.\end{aligned} \tag{32}$$

Evaluating the inner integral, i.e. with respect to x, $\mathcal{I}_1$ can be obtained as (33) at the bottom of this page. This result can be expressed in terms of the EGBMGF as (14), which can be efficiently implemented in Matlab using [32].

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$$\mathcal{I}_1 = \left(\alpha\lambda\right)^{N_1\mu_1+i-k}\frac{1}{\left(2\pi\imath\right)^2}\int_{\mathcal{C}_1}\int_{\mathcal{C}_2}\frac{\Gamma\left(s+r+k-i-N_1\mu_1\right)\Gamma\left(r\right)\Gamma\left(-s\right)}{\Gamma\left(s+r+k-i-N_1\mu_1+1\right)}\left(\frac{1}{\alpha\lambda\Upsilon}\right)^{r}\left(\frac{\Theta\beta}{\alpha}\right)^{s}drds, \tag{33}$$