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Wireless powered UAV relay communications over fluctuating two-ray fading channels

Jiakang Zheng [a,b], Jiayi Zhang [a,b,*], Shuaifei Chen [a], Hui Zhao [c], Bo Ai [d]

[a] School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, PR China
[b] National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, PR China
[c] Communication Systems Department, EURECOM, Sophia, Antipolis 06410, France
[d] State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, PR China

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ABSTRACT

The unmanned aerial vehicle (UAV) relay has recently attracted a large amount of research interests, due to its relative ease of development to enhance cooperative communication performance when the direct link between transmitters and receivers is severely blocked. With simultaneous wireless information and power transfer, the UAV relay can harvest energy from radio frequency and prolong the network lifetime. In this paper, we use the time-switching relaying protocol for UAV energy harvesting (EH) and data forwarding. Different from prior works, the ground-to-air links are modeled as fluctuating two-ray fading channels, which provide a very good fit to the UAV relay communication. In addition, we obtain novel exact analytical expressions for the outage probability, symbol error rate and average capacity of the considered system employing decode-and-forward and amplify-and-forward protocols, respectively. Furthermore, we offer valuable insights into the impact of system and fading parameters on the performance. For example, the optimal EH time can be selected to enhance the system performance. Finally, numerical results are provided to validate the derived results.

1. Introduction

As one of the major research focuses on 5G wireless communications [1,2], the unmanned aerial vehicle (UAV) relay communication has received considerable research interests from both academia and industry due to its tremendous potential in the public and civil domains [3,4]. For example, UAV can provide a reliable wireless relay link between transmitters and receivers, where the direct link is severely blocked by obstacles such as large buildings and hills. However, the UAV relay communication systems are still facing many crucial issues. For instance, the limited capacity of UAV's onboard battery cannot guarantee a continuous high transmit power which may deteriorate the reliability of relay communications. To solve such a practical problem, many existing papers turn to energy-efficient improvement for UAV relay communication systems [5]. Compared with saving energy consumption, harvesting the energy could be a promising alternative. Therefore, the simultaneous wireless information and power transfer (SWIPT) has been proposed as an effective method to replenish the energy of UAV by energy-harvesting (EH) from radio frequency carried both information and energy [6–8]. In addition, the practical non-linear RF energy harvesting model is investigated in [9–11]. Furthermore, the benefits of a potential integration of SWIPT in modern communication networks are discussed in [12]. In order to guarantee the provision of communication services, a solar-powered energy harvesting scheme has been proposed in [13]. However, the intensity of solar energy depending on the flight altitude of the UAV is normally unstable.

On the other hand, relay communications with decode-and-forward (DF) and amplify-and-forward (AF) protocols has been proved to be effective to achieve broader coverage [14,15]. In addition, several EH protocols has been proposed in the literature with diverse degrees of complexity and efficiency. For instance, [16] presented the performance analysis of dual-hop relaying systems with time switching relaying (TSR). The application of SWIPT to the AF relaying system over Rayleigh fading channels has been evaluated in [17], where the outage performance and ergodic capacity expressions were derived. The work in [17] was extended in [18] by considering the DF relaying scheme. Furthermore, the performance of wireless-powered AF and DF relaying in cooperative communications with TSR has been investigated in [19].

However, a majority of the existing papers focuses on conventional stochastic fading channels, such as Gaussian, Rayleigh, Rician and Nakagami-m, which cannot accurately capture the

* School of Electronic and Information Engineering, Beijing Jiaotong University, Beijing 100044, PR China.
E-mail address: zhangjiayi@bjtu.edu.cn (J. Zhang).

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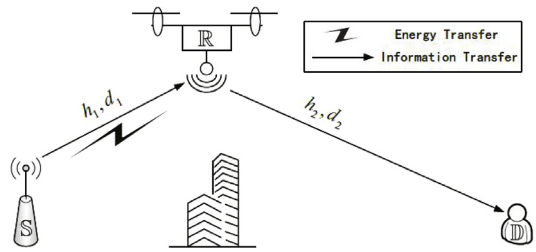

Fig. 1. An UVA relay communication system with SWIPT.

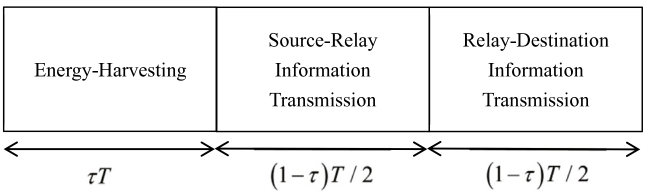

Fig. 2. Dual-hop time-switching relaying protocol.

bimodality of amplitude fluctuations in UAV relay communications [20–22]. Recently, mmWave communication was considered to support high data rate since large available bandwidth can be used in the mmWave frequency band [23]. For instance, [24] demonstrates that UAV carried base stations can offer significant benefits to mmWave backhaul under certain system parameters. It is thus plausible to incorporate UAVs into the 5G mobile communication systems. Furthermore, the fluctuating two-ray (FTR) fading model proposed in [25] offers a very good fit to mmWave communications. As a new generalized fading model, the FTR fading model can capture the wide heterogeneity of random fluctuations of signals over a number of scatterers in mmWave UAV communications. More recently, [26] generalized the FTR fading model with arbitrary positive values of m. Specifically, the application of the FTR fading goes well in many communication systems. For instance, the physical layer security over FTR fading channels has been studied in [27], and the effective capacity over FTR fading channels has been evaluated in [28], respectively. It is worth noting that performance analysis of UAV relay communications with SWIPT over FTR fading channels has not been studied yet.

In order to fill this gap, in this paper, the performance of UAV relay communications with SWIPT over FTR fading channels is investigated, considering both AF and DF protocols. More specifically, the exact analytical expressions for the OP, SER, and AC have been derived. The useful insights on the impact of system and channel parameters can be obtained by the derived results.

2. System model

As illustrated in Fig. 1, let us consider a UAV relay system with a source node ($\mathbb{S}$) and a destination node ($\mathbb{D}$). It is assumed that channel environment on the direct link between node $\mathbb{S}$ and node $\mathbb{D}$ is not favorable for reliable transmission, due to large obstacles such as buildings. To this end, a UAV equipped with a transceiver is operated as a relay node ($\mathbb{R}$) to help wireless transmission. In addition, all nodes have only a single antenna due to weight and energy constraints. The node $\mathbb{S}$ transmits its information with P_s to $\mathbb{D}$ via $\mathbb{R}$. The distances of $\mathbb{S} \to \mathbb{R}$ and $\mathbb{R} \to \mathbb{D}$ links are d_1 and d_2, while h_1 and h_2 denote their channel coefficients, respectively. Due to the limited energy capacity of onboard batteries, we employ SWIPT into the UAV relay communication system.

2.1. Time-switching relaying

Due to its low complexity, it is assumed that the TSR protocol is employed in the UAV relay communication system. As illustrated in Fig. 2, let T denote the total time frame for wireless communication. Based on the time factor τ $(0 \le \tau \le 1)$, the whole time frame is divided into three slots. The energy harvesting time τT is the first period, the second period, $(1-\tau)T/2$, is required for $\mathbb{S} \to \mathbb{R}$ information transmission, and the remaining time is used for $\mathbb{R} \to \mathbb{D}$. In addition, the UAV employs the AF or DF protocol to process and forward the data from $\mathbb{R}$ to $\mathbb{D}$.

When using AF protocol, the instantaneous SNR of $\mathbb{S} \to \mathbb{D}$ at $\mathbb{D}$ can be expressed as

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

where γ_1 and γ_2 represent the instantaneous SNRs of $\mathbb{S} \to \mathbb{R}$ and $\mathbb{R} \to \mathbb{D}$ links, respectively, as [16]

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

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

where $0 < \eta < 1$ is the linear EH efficiency mainly determined by the circuitry at the $\mathbb{R}$ and $2 < \epsilon < 4$ denotes the path loss exponent. In addition, we have the normalized noise $\sigma_1^2 = \sigma_2^2 = 1$ at the $\mathbb{R}$ $\mathbb{D}$. Note that we only consider the time-switching protocol in order to alleviate the employment of the power splitter. However, the analysis framework presented herein can be utilized for the power splitting protocol.

2.2. FTR fading channel

The FTR fading channel is a new statistical channel model composed of two fluctuating specular components with random phases plus a diffuse component. Let $|h_l|^2$, $\forall l \in \{1,2\}$, follow the independent and identically distributed FTR fading channel. The PDF and CDF expressions of $|h_l|^2$ with arbitrary positive values of m are given by [26]

$$f_{|h_l|^2}(x) = \frac{m^m}{\Gamma(m)} \sum_{j=0}^{\infty} \frac{K^j d_j}{j!} f_G\left(x; j+1, 2\sigma^2\right), \tag{4}$$

$$F_{|h_l|^2}(x) = \frac{m^m}{\Gamma(m)} \sum_{j=0}^{\infty} \frac{K^j d_j}{j!} F_G\left(x; j+1, 2\sigma^2\right), \tag{5}$$

where

$$f_G\left(x; j+1, 2\sigma^2\right) \triangleq \frac{x^j}{\Gamma(j+1)\left(2\sigma^2\right)^{j+1}} \exp\left(-\frac{x}{2\sigma^2}\right), \tag{6}$$

$$F_G\left(x; j+1, 2\sigma^2\right) \triangleq \frac{1}{\Gamma(j+1)} \gamma\left(j+1, \frac{x}{2\sigma^2}\right), \tag{7}$$

$$\begin{aligned} d_j \triangleq & \sum_{k=0}^{j} \binom{j}{k} \left(\frac{\Delta}{2}\right)^k \sum_{l=0}^{k} \binom{k}{l} \Gamma(j+m+2l-k) \\ & \times e^{\frac{\pi(2l-k)i}{2}} \left((m+K)^2 - (K\Delta)^2\right)^{\frac{-(j+m)}{2}} \\ & \times P_{j+m-1}^{k-2l} \left(\frac{m+K}{\sqrt{(m+K)^2-(K\Delta)^2}}\right), \end{aligned} \tag{8}$$

where $\gamma(\cdot,\cdot)$ is the incomplete gamma function [29, Eq. (8.350.1)] and $P(\cdot)$ denotes the Legendre function of the first kind [29, Eq. (8.702)].

The FTR fading model can be handily expressed by the parameters K and Δ. Moreover, the K parameter is the ratio of the average power of the dominant waves to the average power of the remaining diffuse multipath, while Δ is a parameter varying from 0 to 1 and represents the similarity of two dominant waves. In addition, the FTR fading includes the one-sided Gaussian, Rayleigh, Rician, Nakagami-q, TWDP and Rician shadowed fading as special cases, by changing the parameters m, K and Δ. For example, when the second component is removed, $\Delta = 0$, the FTR reduces to the Rician fading model. Furthermore, $\overline{\gamma}$ represents the received average SNR given as $\overline{\gamma}=(E_b/N_0)\,2\sigma^2\,(1+K)$, where E_b is the energy density and N_0 denotes the noise density. More importantly, it has been pointed out in [26] that only 40 terms are needed to achieve the truncation error less than 10^{-9} in terms of the Kolmogorov–Smirnov goodness-of-fit statistical test.

3. Performance analysis

3.1. Outage probability

We first derive analytical expressions of the ergodic outage probability for the considered system with both DF and AF protocols. P_{out} denotes the probability that the instantaneous capacity $C(\gamma)$ is less than the predetermined threshold C_{th}. With the TSR protocol, the information transmission only occurs during the second and third period. Therefore, $C(\gamma)$ can be expressed as

$$C\left(\gamma\right)=\frac{1-\tau}{2}\log_2\left(1+\gamma\right), \tag{9}$$

where γ represents the instantaneous SNR.

3.1.1. OP analysis of DF systems

For DF relaying, the OP happens when one of both links' instantaneous capacity falls below the predetermined threshold. Mathematically speaking, the OP can be written as

$$P_{\rm out}^{\rm DF}\left(C_{\rm th}\right)=\Pr\left\{\min\left\{C\left(\gamma_1\right),C\left(\gamma_2\right)\right\}<C_{\rm th}\right\}. \tag{10}$$

With the help of (2), (3) and (9) and assuming $|h_1|^2=X$, $|h_2|^2=Y$, (10) can be rewritten as

$$\begin{aligned}P_{\rm out}^{\rm DF}\left(C_{\rm th}\right)&=1-\Pr\left\{X\geq\alpha\lambda,\,Y\geq\frac{\beta\lambda}{X}\right\}\\&=1-\int_{\alpha\lambda}^{\infty}f_X\left(x\right)\overline{F_Y}\left(\frac{\beta\lambda}{x}\right)dx,\end{aligned} \tag{11}$$

where $\lambda\triangleq2^{\frac{2C_{\rm th}}{1-\tau}}-1$ and $\overline{F_y}$ is the complementary CDF defined as $\overline{F_y}=1-F_y$. Substituting (4) and (5) into (11), we have

$$\begin{aligned}P_{\rm out}^{\rm DF}\left(C_{\rm th}\right)=&1-\frac{m^m}{\Gamma\left(m\right)}\sum_{j=0}^{\infty}\frac{K^jd_j}{j!}\underbrace{\int_{a\lambda}^{\infty}f_G\left(x;j+1,2\sigma^2\right)dx}_{I_1}\\&+\frac{m^{2m}}{\left(\Gamma\left(m\right)\right)^2}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\frac{K^{j+k}d_jd_k}{j!k!\Gamma\left(j+1\right)\Gamma\left(k+1\right)\left(2\sigma^2\right)^{j+1}}\\&\times\underbrace{\int_{a\lambda}^{\infty}x^j\exp\left(-\frac{x}{2\sigma^2}\right)\gamma\left(k+1,\frac{\beta\lambda}{2\sigma^2x}\right)dx}_{I_2}.\end{aligned} \tag{12}$$

In order to obtain the exact expression of $P_{\rm out}^{\rm DF}(C_{\rm th})$, we have the following Lemma.

Lemma 1. *For the UAV relay system with SWIPT and DF protocols, the OP is given as*

$$\begin{aligned}P_{out}^{DF}\left(C_{th}\right)=&1-\frac{m^m}{\Gamma\left(m\right)}\sum_{j=0}^{\infty}\frac{K^jd_j\Gamma\left(j+1,\frac{a\lambda}{2\sigma^2}\right)}{j!\Gamma\left(j+1\right)}\\&+\frac{m^{2m}}{\left(\Gamma\left(m\right)\right)^2}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\frac{K^{j+k}d_jd_k}{j!j!k!\left(2\sigma^2\right)^{j+1}}\\&\times\left(\begin{aligned}&\left(2\sigma^2\right)^{j+1}\Gamma\left(j+1,\frac{a\lambda}{2\sigma^2}\right)\\&-\sum_{s=0}^{k}\left(\frac{\beta\lambda}{2\sigma^2}\right)^s\frac{\left(\alpha\lambda\right)^{j-s+1}}{s!}G_{1,1;1,0;0,1}^{0,1;0,1;1,0}\left(\begin{matrix}s-j-1\\s-j\end{matrix}\middle|\begin{matrix}1\\-\end{matrix}\middle|\begin{matrix}-\\0\end{matrix}\middle|\frac{2\sigma^2}{\alpha\lambda},\frac{\beta}{2\sigma^2\alpha}\right)\end{aligned}\right),\end{aligned} \tag{13}$$

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 G-function [30].

Proof. Please see Appendix A.

While the received average SNR $\bar{\gamma}\rightarrow\infty$ at the first and second links. The asymptotic CDF and PDF of $|h_l|^2$ for $2\sigma^2\gg0$ are given by [31]

$$F_{|h_l|^2}^{\infty}\left(x\right)=\frac{m^md_0x}{\Gamma\left(m\right)}\left(2\sigma^2\right)^{-1}+o\left(\left(2\sigma^2\right)^{-2}\right)\propto\left(2\sigma^2\right)^{-1}, \tag{14}$$

$$f_{|h_l|^2}^{\infty}\left(x\right)=\frac{m^md_0}{\Gamma\left(m\right)}\left(2\sigma^2\right)^{-1}+o\left(\left(2\sigma^2\right)^{-2}\right)\propto\left(2\sigma^2\right)^{-1}, \tag{15}$$

where $o\left(\cdot\right)$ represents the higher order term. Utilizing the method in [32], for a large value of received average SNR $(2\sigma^2)$, the outage probability of the DF dual-hop system is given as $P_{\rm out}^{\rm DF}\propto\left(2\sigma^2\right)^{-2}$ from (11). The slope of the outage probability curve at the high-SNR region is $-\ln P_{\rm out}^{\rm DF}/\ln\left(2\sigma^2\right)=2$. Therefore, the diversity order of the considered DF dual-hop system is 2.

3.1.2. OP analysis of AF systems

For AF relaying, the OP is described as the probability that the instantaneous capacity of the end-to-end link falls below the predetermined threshold. Therefore, it can be expressed as

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

With the help of (1) and (9), the OP can be obtained as

$$P_{\rm out}^{\rm AF}\left(C_{\rm th}\right)=\int_0^{\infty}f_Y\left(y\right)F_X\left(\alpha\lambda+\frac{\beta\lambda}{y}\right)dy. \tag{17}$$

Lemma 2. *For the UAV relay system with SWIPT and AF protocols, the OP is given as*

$$\begin{aligned}P_{out}^{AF}\left(C_{th}\right)=&1-2e^{-\frac{\alpha\lambda}{2\sigma^2}}\frac{m^{2m}}{\left(\Gamma\left(m\right)\right)^2}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\sum_{s=0}^{k}\sum_{t=0}^{s}\binom{s}{t}\\&\times\frac{K^{j+k}d_jd_k\alpha^{s-t}\beta^{\frac{j+t+1}{2}}\lambda^{\frac{j+2s-t+1}{2}}}{j!s!\Gamma\left(j+1\right)\Gamma\left(k+1\right)\left(2\sigma^2\right)^{j+s+1}}\mathrm{K}_{j-t+1}\left(\frac{\sqrt{\beta\lambda}}{\sigma^2}\right).\end{aligned} \tag{18}$$

where $K_v(\cdot)$ is the modified Bessel functions of imaginary argument defined as [29, Eq. (8.407)].

Proof. Please see Appendix B.

Following similar steps of the DF dual-hop system, the diversity order of the considered AF dual-hop system also can be obtained as 2.

3.2. Symbol error rate

In this subsection, we derive the SER expressions of the considered system. For various of modulation formats, the SER is given by [33].

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

where the CDF of the instantaneous SNR is given as

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

Compared with the definition of λ in (11), it can be directly obtained from (13) and (18) by substituting γ into λ.

In addition, a and b are modulation-specific parameters of binary modulation format. For instance, $(a,b) = (1, 0.5)$ for BFSK with orthogonal signaling, $(a,b) = (0.5, 0.5)$ for coherent binary frequency shift keying and $(a,b) = (1,1)$ for differential BPSK [34].

3.2.1. SER analysis of DF systems

Utilizing (19), (20) and (13) for UAV relay systems with SWIPT and the DF protocols, the SER can be written as

$$\begin{aligned}P_{\text{SER}}^{\text{DF}} &= \frac{1}{2} - \frac{1}{2}\sqrt{\frac{1}{\pi}}\frac{m^m}{\Gamma(m)}\sum_{j=0}^{\infty}\frac{K^j d_j}{j!\Gamma(j+1)}\\ &\times \underbrace{\int_0^{\infty}\frac{e^{-\gamma}}{\sqrt{\gamma}}\Gamma\left(j+1,\frac{a\gamma}{2\sigma^2}\right)d\gamma}_{I_4} + \frac{1}{2\sqrt{\pi}}\frac{m^{2m}}{(\Gamma(m))^2}\\ &\times \sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\frac{K^{j+k}d_j d_k}{j!\Gamma(j+1)\Gamma(k+1)(2\sigma^2)^{j+1}}\underbrace{\int_0^{\infty}\frac{e^{-\gamma}}{\sqrt{\gamma}}I_3 d\gamma}_{I_5},\end{aligned} \tag{21}$$

where

$$\begin{aligned}I_3 &\triangleq (2\sigma^2)^{j+1}\Gamma\left(j+1,\frac{a\gamma}{2\sigma^2}\right) - \sum_{s=0}^{k}\left(\frac{\beta\gamma}{2\sigma^2}\right)^s\frac{(\alpha\gamma)^{j-s+1}}{s!}\\ &\times G_{1,1;1,0;0,1}^{0,1;0,1;1,0}\left(\begin{matrix}s-j-1\\ s-j\end{matrix}\middle|\begin{matrix}1\\ -\end{matrix}\middle|\begin{matrix}-\\ 0\end{matrix}\middle|\frac{2\sigma^2}{\alpha\gamma},\frac{\beta}{2\sigma^2\alpha}\right).\end{aligned} \tag{22}$$

Employing [29, Eq. (6.455.1)] and [29, Eq. (3.351.3)] to calculate the integrals I_4 and I_5, we can obtain the analytical expression of the SER for DF relaying systems as

$$\begin{aligned}P_{\text{SER}}^{\text{DF}} &= \frac{1}{2} - \frac{m^m}{\sqrt{\pi}\Gamma(m)}\sum_{j=0}^{\infty}\frac{K^j d_j\left(\frac{a}{2\sigma^2}\right)^{j+1}\Gamma\left(j+\frac{3}{2}\right)}{j!\Gamma(j+1)\left(\frac{a}{2\sigma^2}+1\right)^{j+\frac{3}{2}}}{}_2\\ &\times F_1\left(1, j+\frac{3}{2};\frac{3}{2};\frac{2\sigma^2}{a+2\sigma^2}\right)\\ &+ \frac{m^{2m}}{2\sqrt{\pi}(\Gamma(m))^2}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\frac{K^{j+k}}{j!}\frac{d_j d_k}{\Gamma(j+1)\Gamma(k+1)(2\sigma^2)^{j+1}}\\ &\times\left(\begin{matrix}\frac{2a^{j+1}\Gamma\left(j+\frac{3}{2}\right)}{\left(\frac{a}{2\sigma^2}+1\right)^{j+\frac{3}{2}}}{}_2F_1\left(1,j+\frac{3}{2};\frac{3}{2};\frac{2\sigma^2}{a+2\sigma^2}\right)\\ -\sum_{s=0}^{k}\left(\frac{\beta}{2\sigma^2}\right)^s\frac{\alpha^{j-s+1}}{s!}G_{1,1;1,1;0,1}^{0,1;1,1;1,0}\left(\begin{matrix}s-j-1\\ s-j\end{matrix}\middle|\begin{matrix}1\\ j+\frac{3}{2}\end{matrix}\middle|\begin{matrix}-\\ 0\end{matrix}\middle|\frac{2\sigma^2}{\alpha},\frac{\beta}{2\sigma^2\alpha}\right)\end{matrix}\right),\end{aligned} \tag{23}$$

where ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gauss hypergeometric function [29, Eq. (9.14.2)].

3.2.2. SER analysis of AF systems

For the considered system with the AF protocol, we substitute (18) and (20) into (19) to derive the exact analytical SER expression as

$$\begin{aligned}P_{\text{SER}}^{\text{AF}} &= \frac{1}{2} - \frac{1}{2}\sqrt{\frac{1}{\pi}}\frac{m^{2m}}{(\Gamma(m))^2}\\ &\times \exp\left(\frac{\beta}{8\sigma^4+4\alpha\sigma^2}\right)\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\sum_{s=0}^{k}\sum_{t=0}^{s}\frac{K^{j+k}}{j!s!}\\ &\times \frac{d_j d_k \alpha^{s-t}\beta^{\frac{j+t}{2}}(a+2\sigma^2)^{-\frac{j-t+2s+1}{2}}}{\Gamma(j+1)\Gamma(k+1)(2\sigma^2)^{\frac{j+t-1}{2}}}\Gamma\left(j-t+s+\frac{3}{2}\right)\\ &\times \Gamma\left(s+\frac{1}{2}\right)\binom{s}{t}W_{-\frac{j-t+2s+1}{2},\frac{j-t+1}{2}}\left(\frac{\beta}{4\sigma^4+2\alpha\sigma^2}\right),\end{aligned} \tag{24}$$

where $W_{\lambda,\mu}(\cdot)$ is the Whittaker function [29, Eq. (9.22)].

3.3. Average capacity

The average capacity per unit bandwidth is defined as the expectation of the momentary mutual information, which can be written in the term of the CDF $F(\gamma)$ as [35,36]

$$\overline{C} = \frac{1-\tau}{2\ln 2}\int_0^{\infty}\frac{1-F(\gamma)}{1+\gamma}d\gamma. \tag{25}$$

3.3.1. AC analysis of DF systems

Employing (25) and the $F(\gamma)$ of DF relaying systems, the AC in DF relaying systems can be written as

$$\begin{aligned}\overline{C^{\text{DF}}} &= \frac{1-\tau}{2\ln 2}\frac{m^m}{\Gamma(m)}\sum_{j=0}^{\infty}\frac{K^j d_j}{j!\Gamma(j+1)}\\ &\times \underbrace{\int_0^{\infty}\frac{1}{1+\gamma}\Gamma\left(j+1,\frac{a\gamma}{2\sigma^2}\right)d\gamma}_{I_6} - \frac{1-\tau}{2\ln 2}\frac{m^{2m}}{(\Gamma(m))^2}\\ &\times \sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\frac{K^{j+k}d_j d_k}{j!\Gamma(j+1)\Gamma(k+1)(2\sigma^2)^{j+1}}\underbrace{\int_0^{\infty}\frac{1}{1+\gamma}I_3 d\gamma}_{I_7}.\end{aligned} \tag{26}$$

With the help of [29, Eq. (8.352.2)], [29, Eq. (3.383.10)], [29, Eq. (3.194.3)] and [29, Eq. (8.384.1)], we can calculate the integrals I_6 and I_7 to obtain the analytical expression of the AC as

$$\begin{aligned}\overline{C^{\text{DF}}} &= \frac{1-\tau}{2\ln 2}\frac{m^m}{\Gamma(m)}e^{\frac{\alpha}{2\sigma^2}}\sum_{j=0}^{\infty}\sum_{\rho=0}^{j}\frac{K^j d_j}{\Gamma(j+1)}\left(\frac{\alpha}{2\sigma^2}\right)^{\rho}\Gamma\left(-\rho,\frac{a}{2\sigma^2}\right)\\ &- \frac{1-\tau}{2\ln 2}\frac{m^{2m}}{(\Gamma(m))^2}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\frac{K^{j+k}}{j!}\frac{d_j d_k}{\Gamma(j+1)\Gamma(k+1)(2\sigma^2)^{j+1}}\\ &\times\left(\begin{matrix}(2\sigma^2)^{j+1}e^{\frac{\alpha}{2\sigma^2}}\sum_{\rho=0}^{j}j!\left(\frac{\alpha}{2\sigma^2}\right)^{\rho}\Gamma\left(-\rho,\frac{a}{2\sigma^2}\right)\\ -\sum_{s=0}^{k}\frac{\alpha^{j-s+1}}{s!}\left(\frac{\beta}{2\sigma^2}\right)^s G_{1,1;2,1;0,1}^{0,1;1,2;1,0}\left(\begin{matrix}s-j-1\\ s-j\end{matrix}\middle|\begin{matrix}1-j-1\\ -j-1\end{matrix}\middle|\begin{matrix}-\\ 0\end{matrix}\middle|\frac{2\sigma^2}{\alpha\gamma},\frac{\beta}{2\sigma^2\alpha}\right)\end{matrix}\right).\end{aligned} \tag{27}$$

3.3.2. AC analysis of AF systems

Following a similar approach to derive (27), the AC of the UAV relay system with the AF protocol can be expressed as

$$\begin{aligned}\overline{C^{\text{AF}}} &= \frac{1-\tau}{\ln 2}\frac{m^{2m}}{(\Gamma(m))^2}\sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\sum_{s=0}^{k}\sum_{t=0}^{s}\binom{s}{t}\\ &\times \frac{\alpha^{s-t}\beta^{\frac{j+t+1}{2}}K^{j+k}d_j d_k}{j!s!\Gamma(j+1)\Gamma(k+1)(2\sigma^2)^{j+s+1}}\\ &\times \underbrace{\int_0^{\infty}\frac{1}{1+\gamma}\gamma^{\frac{j+2s-t+1}{2}}e^{-\frac{\alpha\gamma}{2\sigma^2}}K_{j-t+1}\left(\frac{\sqrt{\beta\gamma}}{\sigma^2}\right)d\gamma}_{I_8}.\end{aligned} \tag{28}$$

Utilizing the method to the one presented in [37], we can solve the integral I_8, and (28) can be further written as

$$\overline{C^{\text{AF}}} = \frac{1-\tau}{2\ln 2}\frac{m^{2m}}{(\Gamma(m))^2}$$

Table 1
Required terms for the derived expressions with the truncation error less than 10^{-5}.

	DF	AF
OP	40	40
SER	10	10
AC	10	10

$$\times \sum_{j=0}^{\infty}\sum_{k=0}^{\infty}\sum_{s=0}^{k}\sum_{t=0}^{s} \frac{K^{j+k} d_j d_k \alpha^{s-t} \beta^{\frac{j+t+1}{2}}}{j!s!\Gamma(j+1)\Gamma(k+1)\left(2\sigma^2\right)^{j+s+1}} \times \binom{s}{t} G^{1,1;1,0;2,0}_{1,1;0,1;0,2}\left(\begin{array}{c} -\frac{j+2s-t+1}{2} \\ -\frac{j+2s-t+1}{2} \end{array} \middle| \begin{array}{c} - \\ 0 \end{array} \middle| \begin{array}{c} - \\ \frac{j-t+1}{2}, -\frac{j-t+1}{2} \end{array} \middle| \frac{\alpha}{2\sigma^2}, \frac{\alpha}{4\sigma^4} \right). \tag{29}$$

4. Numerical results

In order to demonstrate the expressions derived in Section 3, numerical results of the considered system performance are presented in this section, along with Monte Carlo simulations. In addition, all nodes require a short distance between the transmitter and the receiver in the energy harvesting scheme, but the distance can be improved by employing multiple antenna. According to the simulation parameters in [38], we use the following set of parameters: $P_s = 20$ W, $d_1 = d_2 = 3$ m, $\sigma^2 = 1$, $C_{\text{th}} = 0.1$ bit/s/Hz, and other parameters vary as the case may be. Note that the number of the required terms for the convergence of all derived expressions is given in Table 1. It is clear to see that only less than 40 terms are needed to achieve the required error (e.g., 10^{-5}).

Fig. 3 depicts the analytical and simulation OP against the time factor τ for different values of the channel parameter m. It is clear to see that analytical results coincide with the Monte Carlo simulation results, which validates the correctness of our derived mathematical expressions. As it can be readily observed, OP significantly decreases with the increasing channel fluctuations m. Therefore, we can obtain the conclusion that have a larger value of m is propitious to reduce the influence of the FTR channel fading. In addition, it is clear that the OP of DF is less than the one of AF. This is expected since AF relaying systems amplify both received information and noise in the same time, however DF relaying systems only enhance the received information. Meanwhile, the minimum OP can be observed by changing τ from 0 to 1, which represents the time of energy harvest. More specifically, both $\tau = 0$ (no energy harvest) and $\tau = 1$ (no information transmission) result in the communication failure completely.

Fig. 4 illustrates the effect of τ on the SER of UAV relay systems with AF protocol for different values of Δ. As it can be observed, the SER is a decreasing function of the value τ. Furthermore, it can be observed that SER decreases when the parameter Δ decreases from 1 to 0. The reason is that larger value of τ denotes greater energy for UAV to transmit information correctly. Besides, increasing Δ indicates the greater phase difference between two dominant waves, which makes the FTR fading channel unfavorable.

The impact of the time factor τ and K on the AC of the considered system is demonstrated in Fig. 5. As similar in Fig. 3, $\tau = 0$ and $\tau = 1$ can both induce to the communication failure completely, which makes the AC reduce to zero. Extensive numerical results have demonstrated that the received SNR become larger with the increase of the value K. For example, the AC for the case of $K = 5$ is larger than the one of $K = 3$.

Fig. 6 depicts the analytical and simulation OP against the distance d_1 ($d_2 = d_1, \tau = 0.5$) for different values of K and

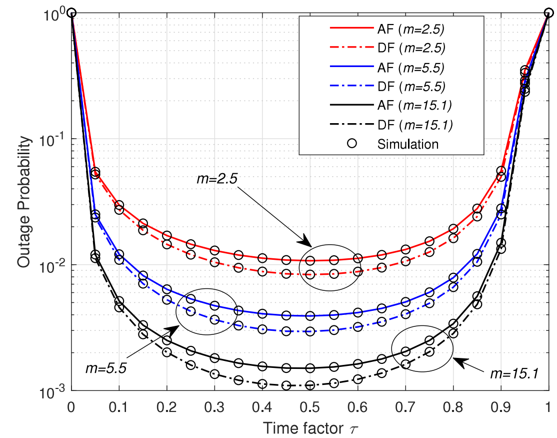

Fig. 3. OP versus τ with different values of m ($K = 6$ and $\Delta = 0.1$).

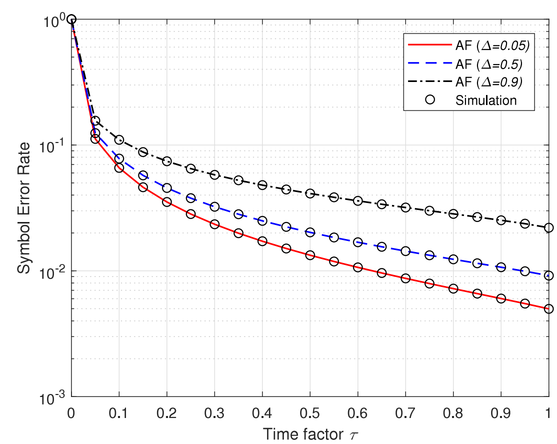

Fig. 4. SER versus τ with different values of Δ ($m = 25$ and $K = 3$).

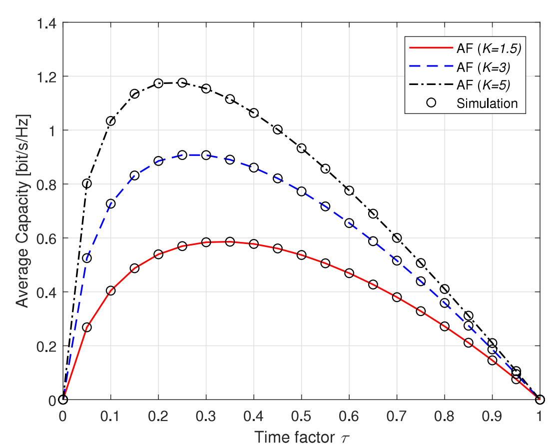

Fig. 5. AC versus τ with different values of K ($m = 25.5$ and $\Delta = 0.1$).

Δ. It is clear that OP increases with the increasing value of the distance d_1. Moreover, OP with AF protocol is higher than DF. As it can be observed, decreasing the parameter K and increasing the parameter Δ can both increase the value of OP.

Fig. 7 illustrates the effect of d_1 ($d = 10$ m, $d_2 = d - d_1, \tau = 0.7$) on the SER of UAV relay systems with AF protocol for different values of K and m. It can be readily observed that the SER increases with the increasing value of d_1 when the distance

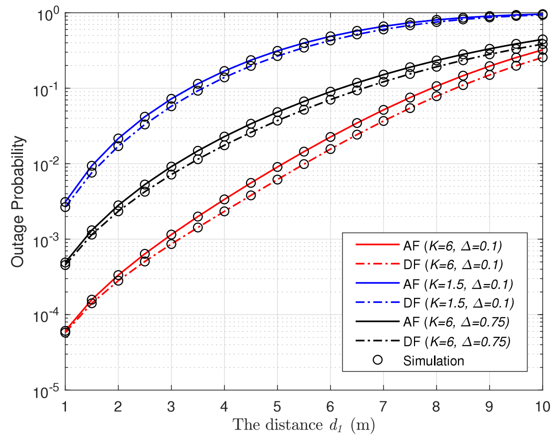

Fig. 6. OP versus d_1 with different values of K and Δ ($m = 15.1$).

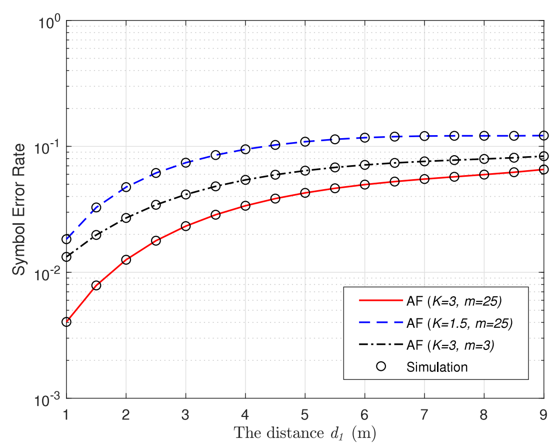

Fig. 7. SER versus d_1 with different values of K and m ($\Delta = 0.1$).

between the source and the destination d is invariant. The reason is that less value of d_1 makes the UAV acquire more energy to transmit information. In addition, decreasing the parameters K and m will lead to the decline in the quality of wireless communications.

5. Conclusion

In this paper, we investigate the performance of the UAV relay system with SWIPT over FTR fading channels. More specifically, we obtain novel and exact analytical expressions for the OP, SER and AC with both DF and AF protocols. The analytical expressions presented in this paper compute efficiently, and can include previous expressions as special cases. Our derived results show that we can significantly improve the performance of the considered system by selecting the optimal values of the parameters τ, d_1, m, Δ and K. As it is evident, an optimal value of τ exists for the best system performance. Furthermore, it confirms the common belief that the DF relay can achieve better performance than the one of the AF relay.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Proof of lemma 1

With the help of [29, Eq. (3.351.2)], I_1 can be readily calculated as

$$I_1 = \frac{1}{\Gamma(j+1)} \Gamma\left(j+1, \frac{a\lambda}{2\sigma^2}\right). \tag{A.1}$$

In order to derive I_2, we first use [29, Eq. (8.352.1)] to divide the Gamma function into two parts. Furthermore, I_2 can be written as

$$I_2 = k! \int_{a\lambda}^{\infty} x^j \exp\left(-\frac{x}{2\sigma^2}\right) dx - k! \sum_{s=0}^{k} \left(\frac{\beta\lambda}{2\sigma^2}\right)^s \frac{1}{s!} \int_{a\lambda}^{\infty} x^{j-s} e^{-\frac{x}{2\sigma^2} - \frac{\beta\lambda}{2\sigma^2 x}} dx. \tag{A.2}$$

Employing [29, Eq. (3.351.2)] and the resolvent of the second integral form (A.2) in [37], we can directly obtain the exact expression of I_2 as below.

$$I_2 = k! (2\sigma^2)^{j+1} \Gamma\left(j+1, \frac{a\lambda}{2\sigma^2}\right) - k! \sum_{s=0}^{k} \left(\frac{\beta\lambda}{2\sigma^2}\right)^s \frac{(\alpha\lambda)^{j-s+1}}{s!} \times G^{0,1;0,1;1,0}_{1,1;1,0;0,1}\left(\begin{matrix} s-j-1 \\ s-j \end{matrix} \middle| \begin{matrix} 1 \\ - \end{matrix} \middle| \begin{matrix} - \\ 0 \end{matrix} \middle| \frac{2\sigma^2}{\alpha\lambda}, \frac{\beta}{2\sigma^2\alpha}\right). \tag{A.3}$$

The proof is finished by substituting (A.1) and (A.3) into (12).

Appendix B. Proof of lemma 2

Firstly, we can express the OP of AF (16) in another form as

$$P_{out}^{AF}(C_{th}) = 1 - \Pr\left\{X > \alpha\lambda + \frac{\beta\lambda}{Y}\right\} = 1 - \int_0^{\infty} f_Y(y) \overline{F_X}\left(\alpha\lambda + \frac{\beta\lambda}{y}\right) dy. \tag{B.1}$$

Substituting both (4) and (5) into (17) and (B.1), and utilizing [29, Eq. (8.352.1)], [29, Eq. (3.351.3)], [29, Eq. (1.111)] and [29, Eq. (3.471.9)], we can derive two equal results with different forms. Then, subtracting two formulas, we can obtain the following properties.

$$\frac{m^m}{\Gamma(m)} \sum_{j=0}^{\infty} \frac{K^j d_j}{\Gamma(j+1)} = 1, \tag{B.2}$$

$$\frac{m^{2m}}{(\Gamma(m))^2} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{K^{j+k} d_j d_k}{\Gamma(j+1)\Gamma(k+1)} = 1, \tag{B.3}$$

which are used to complete the proof.

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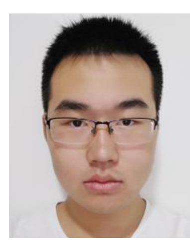

Jiakang Zheng, received the B.Eng. degree in communication engineering from Beijing Jiaotong University, China, in 2019. He is currently pursuing the Ph.D. degree in Beijing Jiaotong University. His main research interests include performance analysis of wireless systems. 15211085@bjtu.edu.cn

Jiayi Zhang, received the B.Sc. and Ph.D. degrees in communication engineering from Beijing Jiaotong University, China, in 2007 and 2014, respectively. From 2014 to 2015, he was a Humboldt Research Fellow with University of Erlangen-Nuermberg, Germany. Since 2016, he has been a Professor with Beijing Jiaotong University. His main research interests include massive MIMO and generalized fading channels. From 2017, he serves as an Associate Editor of the IEEE COMMUNICATIONS LETTERS and the IEEE ACCESS. jiayizhang@bjtu.edu.cn

Shuaifei Chen, received the B.Sc. in communication engineering from Beijing Jiaotong University, China, in 2018. From 2018, he is a Ph.D. student in Beijing Jiaotong University. His main research interests include performance analysis of wireless systems.14221092@bjtu.edu.cn

Hui Zhao, received the B.Sc. in telecommunications engineering from Southwest University, Chongqing, China, in 2016, and the M.S. degree in electrical engineering, from King Abdullah University of Science and Technology, Thuwal, Saudi Arabia, in 2019, He is currently a Ph.D. student in communication systems, EURECOM, Sophia Antipolis, France. His main research interests include performance analysis of wireless systems. hui.zhao@kaust.edu.sa

Bo Ai, received the M.S. and Ph.D. degrees from Xidian University, Xian, China, in 2002 and 2004. He was with Tsinghua University, Beijing, China, where he was an Excellent Postdoctoral Research Fellow in 2007. He is currently a Professor and an Advisor of Ph.D. candidates with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. His current research is channel modeling and 5G mobile communications for railway systems. boai@bjtu.edu.cn