Performance Analysis of a SWIPT Enabled UAV-Assisted Relaying

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Abstract. *In the recent era, unmanned aerial vehicle (UAV) plays an important role in numerous application fields related to the wireless communication system. Due to its precise control, efficient deployment, and affordable cost, UAV-assisted communication attracts significant attention to all the sectors including the defense sector, agriculture sector, and security purpose, and so on. Though UAV-assisted relaying has enormous advantages but there are potential challenges while UAV deploys as a relay. For example, deploying UAV in the wireless communication field, its battery life is the main concern due to its limited battery size and storage capacity. To get significant benefits from UAV while deployed in the cooperative communication network, the battery status of the UAV is an unavoidable issue. To minimize the aforementioned problem, energy harvesting (EH) techniques can be an efficient solution. The UAV can harvest energy from the transmitted power by the source and with the help of this harvested energy UAV can retransmit the signal to the destination. However, there are several parameters that also significantly influence the UAV-based cooperative system performance such as UAV's position, time allocation factor and power allocation factor, and UAV's height. Considering the importance of the aforementioned parameters, in this paper, we have considered simultaneous wireless information and power transfer (SWIPT) enabled UAV-assisted relaying network and evaluate the system outage perfor-mance with different parameters aspects. We have provided some insight about the parameters such as the UAV's position, the power allocation factor and the time allocation factor and the UAV's height by providing simulation results such as the outage probability versus transmit power in the different urban scenario, the outage probability versus time allocation factor and power allocation factor and the outage probability versus UAV's height. These simulation results clearly show the significance of the above-mentioned parameters in wireless-powered UAV-assisted cooperative communication.*

Keywords

1. Introduction

Recently, unmanned aerial vehicle (UAV) draws significant attraction for numerous applications due to their affordable cost, fast deployment, and precise control. Nowadays, UAV provided various facility including disaster monitoring, frontier surveillance, product delivery purpose, any kind of medical emergency, and so on [1]. On the other hand, the utilization of UAV-assisted wireless communications includes various chal-

lenges such as networking architectures, channel characteristics, etc [2]. UAV also served as a flying base station to facilitate wireless coverage in the different geographical areas [3]. UAV can also deploy in 5G technology which could be an important component to provide wireless communication networks with enhanced data rate [4]. However, UAV can also play a potential role in the Internet of Things (IoT) to serve small battery-constraint devices such as sensor networks [5].

2. Related works

At present, numerous research activities are ongoing on UAV-based wireless communication systems. UAV altitude is an important parameter to extend network coverage. In [6], analysis shows that optimum altitude is the function of the statistical parameters of the different urban environments and maximum allowed pathloss. While UAV served as a mobile base station to ensure the coverage to all the ground terminals by placement optimization techniques presented in [7]. Height- dependent path-loss exponent was introduced in [8], which minimizes the system outage probability of an A2G link. Optimum altitudes for both static and mobile UAV are studied in [9]. However, the utilization of multiple UAV can enhance system performance. The capacity increases as the number of UAV increases proportionally showed in [10]. Considering multi UAV relaying [11], the dual-hop multilink scenario provides better performance than the multi-hop single link. Nevertheless, the UAV's Limited energy storage capacity is one of the main concerns while deploying UAV in a wireless cooperative network. Meanwhile, energy harvesting (EH) can be an efficient solution for this problem. UAV-enabled relaying with energy harvesting techniques in the different urban scenarios has been studied in [12]. Simultaneous Wireless Information and Power Transfer (SWIPT) is now one of the potential editions in wireless communication systems. To transfer energy and information to incorporate between smart communications systems, SWIPT plays an important role including 5G technology, IoT technology and mobile edge computing,

and so on. Different SWIPT architecture has been studied in [13] including recent advances and future directions. UAV assisted communication with mmWave SWIPT techniques to provide secrecy performance evaluation studied in [14]. With time splitting (TS) and power splitting (PS) scheme, UAV-assisted decode and forward network were considered to provide closed-form expression of outage and BER with aggregate interference showed in [15]. Considering SWIPT technology in [16], they optimized trajectory profile, PS ratio and power profile to maximize throughput. In our previous work [17], we have considered SWIPT enabled UAV to search optimal UAV position for low altitude base UAV's channel. To find the optimal solution with two steps, first of all we optimized the power splitting factor with given TA then we optimized TA with conditionally optimized power splitting factor expressed in the closed form [18].

Considering the above-mentioned work, we can easily relate that several factors need to be taken into account while utilizes UAV as a relay in a cooperative communication system. Such as UAV's battery status as well as the parameters like the UAV's position, the time allocation factor, the power allocation factor, and the UAV's height which has a significant role in the system performance.

Motivated by the aforementioned performance controlling factors, in this paper, we have designed a UAV-assisted wireless communication system with SWIPT technology. We evaluate the system outage performance with various parameters aspects. We evaluate the system outage performance as a function of UAV's position, power allocation factor and time allocation factor as well as UAV's height which is also a key factor for a reliable UAV-based wireless communication system. Simulation results clearly show that the significance of SWIPT technology in UAV-assisted cooperative networks and as well as the important insight of different performance measuring parameters.

3. System model

We have considered a system illustrated in Fig. 1 with a single base station (S), a mobile station (D) and a UAV which deploys as decode and forward relay. All the nodes are equipped with single antenna. The UAV having altitude H including the ground distance r_1 and r_2 from S, D respectively. The distance between S-to-UAV and UAV-to-D is denoted by d_1, d_2 respectively. While θ_1, θ_2 represent the elevation angle between S to UAV and UAV to D respectively. The relationship between the parameters can be expressed as $\theta_i = \tan^{-1}\frac{H}{r_i}$.
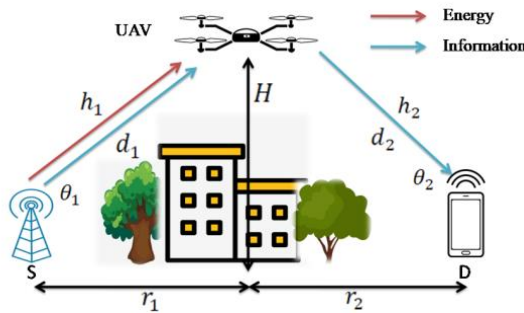

Fig. 1: UAV-assisted cooperative communication.

The wireless channel between S-UAV and UAV-D experienced small-scale fading and large-scale path-loss. Since the receiver experienced LoS and multipath scattering, Rician distribution is the suitable choice to model small-scale fading. The channel fading power can be modeled as

$$X_i = |h_i|^2 \qquad (1)$$

$X_i \sim noncentral \ \chi^2(K_i)$, which can be expressed as [19]

$$f_{X_i}(x) = \frac{(k_i+1)}{\overline{X}_i} e^{-k_i} e^{-\left(\frac{(k_i+1)x}{\overline{X}_i}\right)}$$
$$\times I_o\left(2\sqrt{\frac{(k_i+1)x}{\overline{X}_i}}\right); \quad x \geq 0 \quad (2)$$

where $\overline{X}_i$ is the mean and $I_o(.)$ is the zero order modified Bessel function of first kind [20]; K_i is the Rician factor which is defined as the ratio of the power in LoS and NLoS power in multi-scatters.

Figure 2 represents the system relaying protocols where in phase I, source transmits the signal towards the UAV relay which then harvests energy from the received signal and as well as decodes it at τT time, where $\tau \in (0,1)$. With this harvested energy, the UAV transfers the information to the destination with $(1-\tau)T$ time in the second phase. The power splitting ratio is $(1-\alpha):\alpha$, where $\alpha \in (0,1)$. Without loss of generality, we assume $T=1$ in this system.

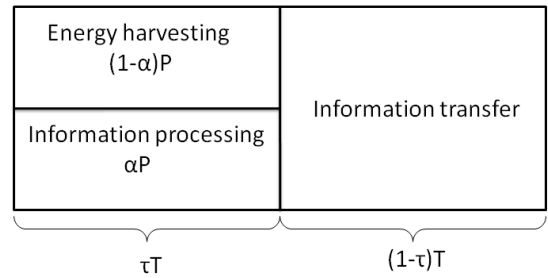**Fig. 2:** System relaying protocols.

The harvested energy at the UAV device can be expressed as

$$E_h = \eta(1-\alpha)P_1 X_1 \tau P L_1^{-1} \qquad (3)$$

where η is the energy harvesting efficiency and P_1 is the transmit power of S. PL_1 is the pathloss between S to UAV which can be expressed as

$$PL_1 = \frac{\eta_{LOS1} - \eta_{NLOS1}}{1 + a_1 e^{-b_1(\theta_1 - a_1)}} + 20\log_{10}\left(\sqrt{r_1^2 + h^2}\right)$$
$$+ 20\log_{10}\left(\frac{4\pi f}{c}\right) + \eta_{NLOS1} \qquad (4)$$

where η_{LOS1}, η_{NLOS1}, a_1, b_1 are the constant parameters belongs to the propagation environment [21]. $c = 3 \times 10^8$ m/s & $f = 2$ GHz is the speed of light and frequency respectively.

The deliverable rate from S to UAV is expressed as

$$R_1 = \tau\log_2\left(1 + \frac{P_1\alpha X_1}{\sigma_1^2 PL_1}\right) \qquad (5)$$

where σ_1^2 is the noise power at UAV.

The deliverable rate from UAV to D is expressed as

$$R_2 = (1-\tau)\log_2\left(1 + \frac{\eta P_1(1-\alpha)\tau X_1 X_2}{\sigma_2^2(1-\tau)PL_1 PL_2}\right) \qquad (6)$$

where $\sigma_2{}^2$ the noise power at D. PL_2 is the path-loss between UAV to D which can be expressed as

$$PL_2 = \frac{\eta_{LOS2} - \eta_{NLOS2}}{1 + a_2 e^{-b_2(\theta_2 - a_2)}} + 20\log_{10}\left(\sqrt{r_2{}^2 + h^2}\right) + 20\log_{10}\left(\frac{4\pi f}{c}\right) + \eta_{NLOS2} \tag{7}$$

where η_{LOS2}, η_{NLOS2}, a_2, b_2 are the constant parameters belonging to the propagation environment.

4. Outage probability analysis

The outage probability of the system considering information rate R_t is given by

$$P_{Out} = \mathrm{P}\left[\min\left(R_1, R_2 < R_t\right)\right] \tag{8}$$

Equation (8) can be further modified as

$$P_{Out} = 1 - \mathrm{P}\left[X_1 \geq \Gamma_1, X_1 X_2 \geq \Gamma_2\right] \tag{9}$$

where, $\Gamma_1 = \dfrac{\left(2^{\frac{R_t}{\tau}} - 1\right)\sigma_1{}^2 PL_1}{P_1\alpha}$ and

$\Gamma_2 = \dfrac{\left(2^{\left(\frac{R_t}{1-\tau}\right)} - 1\right)\sigma_2{}^2(1-\tau)PL_1 PL_2}{\eta P_1\tau(1-\alpha)}$

P_{Out} can be represented as

$$P_{Out} = 1 - \int_{\Gamma_1}^{\infty} F_{X_2}{}^c\left(\frac{\Gamma_2}{u}\right) f_{X_1}(u)\,du \tag{10}$$

where $F_{X_2}{}^c\left(\frac{\Gamma_2}{u}\right)$ is the CCDF of the random variable X_2 which can be given by

$$F_{X_2}{}^c\left(\frac{\Gamma_2}{u}\right) = Q_1\left(\sqrt{2K_2}, \sqrt{\frac{2(1 + K_2)\Gamma_2}{\overline{X_2}u}}\right) \tag{11}$$

where $Q_1(.,.)$ is the first order Marcum Q-function [22]. Now, the pdf of the random variable X_1 is given by

$$F_{X_1}(u) = \frac{(k_1 + 1)}{\overline{X_1}} e^{-k_1} e^{-\left(\frac{(k_1+1)u}{\overline{X_1}}\right)} \times I_o\left(2\sqrt{\frac{(k_1 + 1)u}{\overline{X_1}}}\right) \tag{12}$$

Now substituting (11) and (12) in (10), the outage probability is finally expressed as

$$P_{Out} = 1 - \int_{\Gamma_1}^{\infty}\left(\frac{(k_1 + 1)}{\overline{X_1}} e^{-k_1} e^{-\left(\frac{(k_1+1)u}{\overline{X_1}}\right)}\right.$$
$$\times I_o\left(2\sqrt{\frac{(k_1 + 1)u}{\overline{X_1}}}\right)$$
$$\left.\times Q_1\left(\sqrt{2K_2}, \sqrt{\frac{2(1 + K_2)\Gamma_2}{\overline{X_2}u}}\right)\right)du \tag{13}$$

5. Simulation results

To verify the system performance, various simulation results are shown in this section. We evaluate the system performance with different parameters aspects. To perform the simulation we set up parameters values which are provided in Tab. 1.

Tab. 1: Parameters for simulation.

| Parameter	Description	Value
r_1	Source location	10 m
r_2	Destination location	10 m
α	Power allocation factor	0.5
τ	Time allocation factor	0.5
H	UAV height	10 m
R_t	Target rate	0.5 bit/sec/Hz
$\sigma_1{}^2, \sigma_2{}^2$	Noise power	-104 dBm
η	Energy harvesting efficiency	0.6
P_1	Transmit power	[10-40] dBm

Figure 3 represents outage performance in different urban scenarios as a function of source transmit power. The performance was evaluated with $k_1 = k_2 = 4$ where solid lines indicate analytical results and the marker represents the Monte Carlo simulation results which completely matched with each other. We observe the outage probability performance for urban, sub-

urban, dense urban and highrise environment conditions.
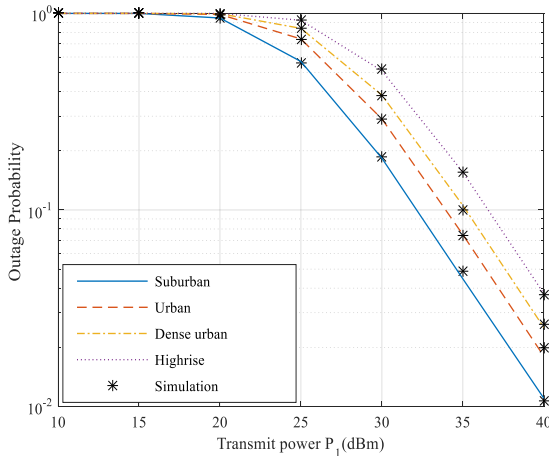
Fig. 3: Outage probability Vs transmits power P_1 for different urban environments.

As expected, the optimal result provided by the suburban scenario due to the better LoS condition from other environment scenarios. Next we show the outage probability versus different Rician factor setup to see the system performance. As we all know, the lower K_1, K_2 values indicate that a more severe fading scenario which reflects in Fig. 4. When $K_1 = K_2 = 1$, the outage performance is worst compared to results with higher K_1, K_2 scenarios.
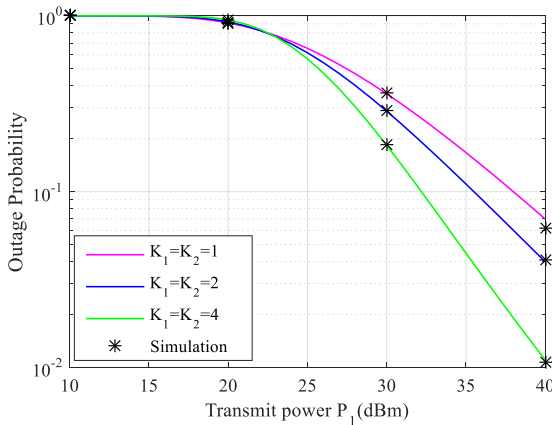
Fig. 4: Outage probability Vs transmits power P_1 for different K_1, K_2 values in suburban environment.

We also extend our simulation results to observe the outage performance for different trans-

mission data rates. For this simulation we set up the parameters as $r_1 = r_2 = H = 10$ m, $K_1 = K_2 = 4$ for the suburban scenario. As we can see from Fig. 5, as the data rate increases the system outage performance degrades. This phenomenon happens as the system failed to maintain the requirements for higher data rate transmission.
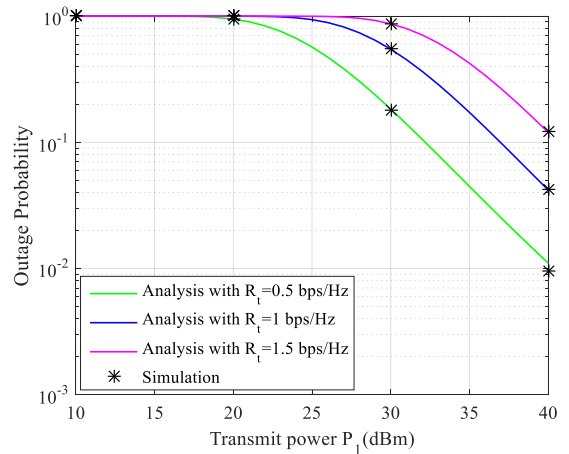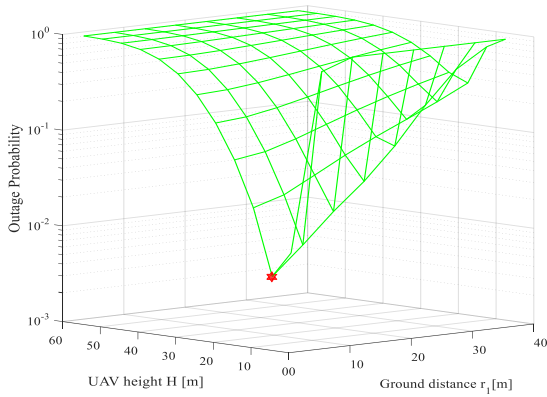

Fig. 5: Outage probability Vs transmits power P_1 for different transmission data rate.

Meanwhile, UAV's position (H, r_1) is the most important parameter which influences the system's performance mostly. To observe the issue, we also represent the outage probability Vs ground distance r_1 and the UAV's height H. As we can see from the Fig. 6 which represents the outage probability varies with different UAV location (H, r_1). From the figure, when the source and the UAV located far from each other, the outage performance is the worst for this scenario.

It clearly indicates that there must be an optimal UAV's position (H, r_1) which can minimize the outage of the network. The marker shows the optimal UAV's location (H, r_1) in Fig. 6.

However, other significant system performance parameters are the time allocation factor and the power allocation factor. To evaluate the influence of those parameters, we provide the outage probability Vs the time allocation and the power allocation factor in Fig. 7 in a suburban environment with transmit power $P_1 = 40$ dBm and $k_1 = k_2 = 4$. From Fig. 7, we can see that

Fig. 6: Outage probability Vs UAV position in suburban scenario with $k_1 = k_2 = 4$ and transmit power $P_1 = 40$ dBm.

when the τ is increasing which means that the UAV gets more time in the harvesting part so that the system performance improves but after a certain value of τ the performance becomes degrade because the UAV failed to retransmit the signal to the destination due to less time allocated to the second phase of transmission. The marker shows the optimal α, τ values set up for this scenario which minimizes system outage. It is obvious that as UAV harvests more energy the system performance will be better.
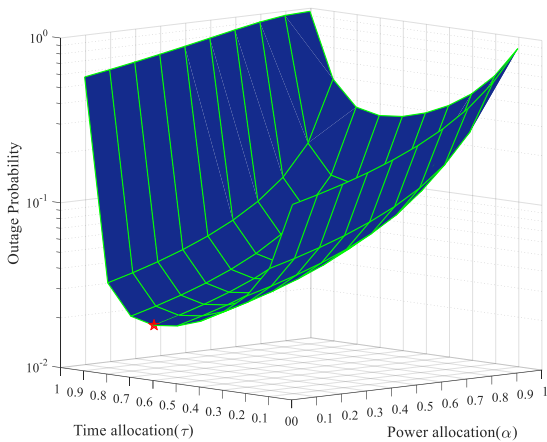
Fig. 7: System outage probability Vs time allocation factor and power allocation factor.

On the other hand, the UAV's height has also a significant impact on the system performance. Considering this issue, we also evaluate the system outage probability as a function of UAV's

height in the different urban scenarios. We can easily observe from Fig. 8 that the outage probability first decreases as UAV's height increases up-to a certain value then the outage probability again increases as UAV's height increases.
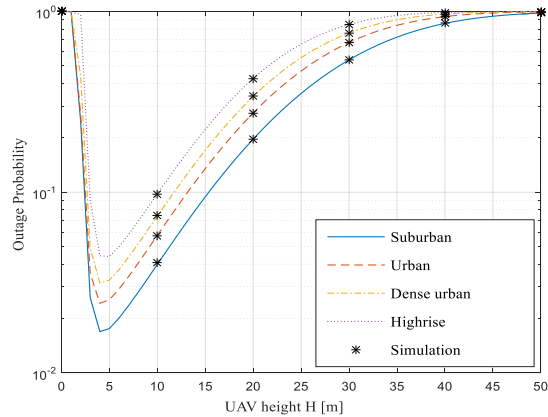
Fig. 8: Outage probability Vs UAV's height in different urban environments with $P_1 = 40$ dBm and $k_1 = k_2 = 4$.

When the UAV's height is very low, because of the NLoS issue the system outage probability is high. But as the UAV's height starts increasing the outage probability decreases. Then suddenly after a certain height, the outage is again increasing due to a higher path loss which indicates that there exists an optimal UAV's height which minimizes the system outage probability.

6. Conclusions

UAV-assisted wireless communication recently gains potential attraction in recent period for its vast benefits and opportunities. However, it provides an enormous advantage where human access is impossible or dangerous. Though the UAV has significant benefits while deploying as a relay but on the other hand the challenges also take into account such as UAV's battery life, precise design, accuracy, etc. Give priority to battery life issues of UAV, numerous researches are ongoing to provide UAV-based communication safer, faster and reliable. Recently SWIPT technology draws significant attention to the researcher. Utilizing SWIPT technology shows major improvement in UAV-assisted wire-

less communication. While UAV deploys as a relay, parameters such as UAV position, time and power allocation factors and, UAV's height need to be considered. In this paper, we summarize the importance of those parameters with SWIPT technology with different simulation results. Our results indicate the convenience of SWIPT enabled UAV-assisted cooperative communication.

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