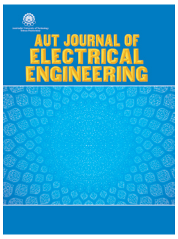

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Throughput Maximization for Multi-Slot Data Transmission via Two-Hop DF SWIPT-Based UAV Systems

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ABSTRACT: In this paper, an Unmanned Aerial Vehicle (UAV) assisted cooperative communication system is studied, wherein a source transmits information to the destination through an energy harvesting decode-and-forward UAV. It is assumed that the UAV can freely move in between the source-destination pair to set up line of sight communications with both nodes. Since the battery of the UAV may be limited, it can harvest energy from the received signal by power splitting technique to be able to perfectly transmit data to the destination. Therefore, we study throughput maximization problem for multiple time slots data transmission through the cooperative energy harvesting UAV. To maximize the throughput, optimal power allocation at the source and the UAV and power splitting ratio at the UAV are studied over each time slot in presence of energy-causality constraints at the UAV. Finally, numerical results are presented to analyze the spectral and energy efficiency of the proposed system, and effects of optimal power allocations and power splitting ratio. The results indicate that by utilizing optimal resource allocations at the source and the UAV, and utilizing Simultaneous Wireless Information and Power Transfer (SWIPT), significant throughput improvement is achieved compared to those without optimal resource allocation or SWIPT. All of static UAV scenarios (i.e., the maximum throughput between the source and the destination) increases, while there is no need to increase the battery capacity of the UAV.

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1- Introduction

Unmanned Aerial Vehicles (UAVs), also known as drones, have gained research interests recently, mainly due to the decrease in building costs and their many applications. UAVs flexibility to provide Line of Sight (LOS) communications, has made them suitable to play the role of mobile relays. They have wide applications such as, improving performance of cellular communications, communicating to the low-cost Internet of Things (IoT) devices, and also the UAVs can form a communication network, and provide infrastructure in emergency situations [1].

UAVs have different categories; They can be classified according to their altitude as high and low altitude platform, or according to their wing as fixed and rotary-wing UAVs [2][3]. UAV placement optimization for minimizing the number of UAVs providing wireless coverage to a group of ground terminals or 3-dimensional (3D) placement for energy efficient maximal coverage, has been considered in [4] and [5], respectively. In [6], a cyclical multiple access scheme is introduced in order to schedule the communications between different ground terminals and a UAV. Additionally, time allocations of different ground terminals are optimized to maximize their minimum throughput.

Different types of UAVs are suitable for different applications. Some of the main applications are briefly discussed in the following [7][8]. For instance, UAV-aided ubiquitous coverage, wherein the UAV works as an off-loader for the base station in a crowded area, or can work as a base station when there is no infrastructure or the infrastructure is not working properly due to natural disasters. UAV-aided data collection and information dissemination are also discussed, wherein UAVs collect data or send information to a wide range of distributed sensors, which is well suited for delay-tolerant applications; UAV-aided relaying, which uses UAVs as relay nodes for situations wherein the direct communications between the source and the destination are blocked or are far from each other and the performance degrades. In [9], performance of the system is analysed by using a UAV as a mobile decode-and-forward (DF) relay, and optimal trajectory of UAV and its power allocation are discussed to maximize the throughput. In [10], the same scenario is considered for an amplify-and-forward (AF) relay. In [11], a lower bound for ergodic capacity is obtained in presence of AF UAVs, and also the effects of number of antennas and the transmit power at the UAV are investigated on the capacity bound.

Despite all the benefits and applications of UAV-assisted communications, it suffers from various challenges [12].

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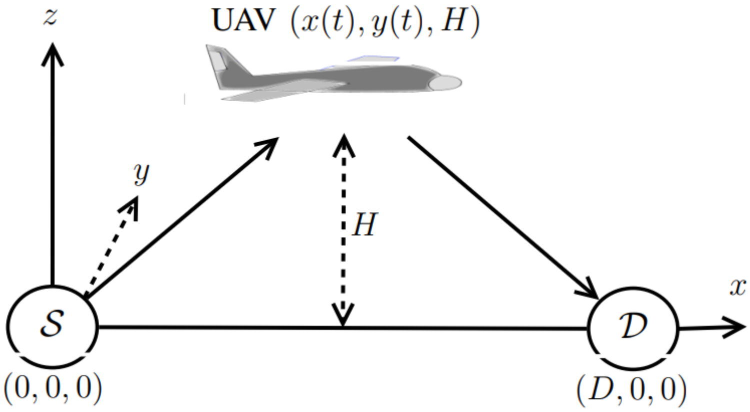

Fig. 1. UAV-assisted SWIPT two-hop communications.

One is the constraints on the operational weight and size of a UAV which limits its lifetime and battery capacity. In order to tackle these issues, [13] and [14] focus on simultaneous information and power transfer at the UAV for DF and AF scenarios, where UAV uses the power gained from radio signal. However, they do not consider data buffer at the UAV and power allocation optimization at the source. [15] optimizes trajectory by jointly considering the communication throughput and the UAVs energy consumption by proposing a theoretical model on a fixed-wing UAV propulsion energy consumption, as a function of its flying speed, direction and acceleration. [16] studies a UAV-enabled mobile relaying system between a ground source and a ground destination, and aims to maximize spectrum efficiency as well as energy efficiency by assuming an energy efficient circular trajectory for the UAV, and employing Time-division Duplexing (TDD) based DF relaying by jointly optimizing the time allocations for the UAVs relaying together with its flying speed and trajectory. Other methods such as using solar panels on UAV can increase the weight, and cause decreasing both the lifetime and the energy efficiency. In [17], a UAV-assisted network is considered, where the UAV acts as an energy source to provide radio frequency energy for multiple energy harvesting-powered Device-to-Device (D2D) pairs. Afterwards, the throughput is maximized while the energy causality constraint under a harvest-transmit-store model is satisfied. Another challenge is to provide secure and reliable communication links. Due to the broadcast and LOS nature of the UAV's communication links, it is of importance to consider the physical layer secrecy of the links. In [18], the average secrecy rates of the UAV-to-ground and ground-to-UAV transmissions are studied by applying the physical layer security techniques, while in [19], the secrecy rate of a UAV-assisted Simultaneous Wireless Information and Power Transfer (SWIPT) system is investigated in presence of multiple eavesdroppers.

As discussed, to utilize a UAV as a mobile relay, one of the main challenges is the limited capacity of its battery and lifetime. One way to tackle this issue is to utilize SWIPT at the UAV, where the UAV will be able to charge its battery and use this energy to send data toward destination. On the other hand, from the information theoretic points of view, it is known that DF relaying scheme outperforms the AF, especially when the source-destination pair are far away from each other, however, at the cost of more processing at the relay [20]. Therefore, it is assumed in this paper that a full-power source communicates to a destination by a DF SWIPT-based UAV with limited capacity battery over multiple time slot transmissions and data buffer. To maximize the sum rates over the time slots, called the throughput, not only the source but also the UAV must optimally allocate the power over different time slots. The UAV can control its harvesting energy to charge the battery over the time slots, and control the quality of the information recovery by changing the value of the power splitting ratio. The corresponding optimization problem is investigated and optimal resource allocations at the source and UAV are investigated in presence of information and energy causality constraints at the transmitting nodes. In conclusion, throughput and energy efficiency of the system are numerically compared for a mobile/fixed UAV and with/without SWIPT-UAV, to highlight the performance improvement.

The rest of this paper is organized as follows. In Section II, the system model of the UAV enabled wireless relay network with SWIPT is presented. In Section III, the optimization problem to maximize the throughput is formulated. Numerical results are presented in Section IV to characterize the system performance, and the results are compared. Finally, the paper is concluded in Section V.

2- System Model

A cooperative communication wireless system with a fixed source node, S, a fixed destination node, D, and a mobile UAV relay (i.e. a UAV), are illustrated in Fig. 1. It is assumed that the direct link between S-D pair is not possible due to the blockage. Hence, a relay node is needed to set up a wireless communication between S and D. A UAV is used as a cooperative mobile relay which can move between S and

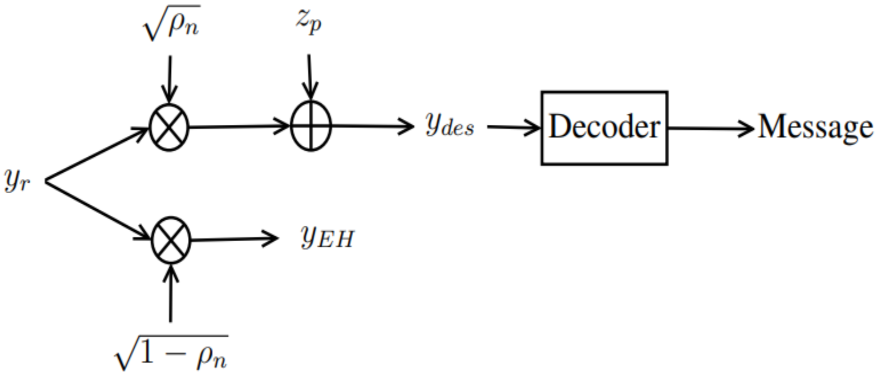

Fig. 2. Block diagram of the UAV's structure for power splitting and re-sending the data to the destination.

D. It is also assumed that the source has energy of E_s, and the UAV has a dedicated energy E_r, but still has a limited battery capacity. Therefore, the UAV may harvest energy from the received signal by using the power splitting technique to recharge its battery and use it for data transmission to the destination.

A three-dimensional Cartesian coordinate system is considered, where S is located at (0, 0, 0) and D is located at (D, 0, 0). The UAV is flying over the air at the fixed altitude H and its location at each slot is expressed as (x(t), y(t), H), $0 \le t \le T$, where x(t) and y(t) denote the time-varying location of UAV in x− and y− coordinates, respectively. T is the whole performance time of the system. Total performance time T is divided into N equally spaced time slots (i.e. $T = N\delta_t$), where δ_t denotes duration of each time slot, and n = 1, 2, ...N indicates the label of time slots. In order to assume a fixed location for UAV within each time slot, δ_t is chosen sufficiently small. The UAV travels in a direct trajectory from S to D at altitude H, which is the minimum relative distance between S and D. Hence, the distance between the source and the UAV is $d_{sr}[n]=\sqrt{x^2[n]+y^2[n]+H^2}$ at each time slot, and $d_{rd}[n]=\sqrt{(D-x[n])^2+y^2[n]+H^2}$ denotes the distance between the UAV and the destination. Since there is a LOS link between the UAV and both nodes, over time slot n, the channel coefficients for S-UAV and UAV-D are given by:

$$h_{sr}[n]=\sqrt{\beta_0 d_{sr}^{-2}[n]}=\sqrt{\frac{\beta_0}{x^2[n]+y^2[n]}+H^2}, \tag{1}$$

$$h_{rd}[n]=\sqrt{\beta_0 d_{rd}^{-2}[n]}=\sqrt{\frac{\beta_0}{(D-x[n])^2+y^2[n]}+H^2}, \tag{2}$$

Where β_0 indicates the power loss at the reference distance $d_0 = 1$.

Therefore, at the n-th time slot, the received signal from source at the UAV is expressed as:

$$y_r[n]=h_{sr}[n]x_s[n]+z_r[n],\ \forall n=1,2,...,N, \tag{3}$$

Where x_s is the transmitted signal from the source with $\mathbb{E}(|x_s[n]|^2)=p_s[n]$, and $z_r \sim \mathcal{CN}(0,N_r)$ models the Additive White Gaussian Noise (AWGN). Note that $\mathbb{E}(.)$ indicates the statistical average.

The UAV not only decodes the received signal, but also does harvest the energy. Therefore, the received signal at the UAV is divided into two parts; One part for information decoding (i.e. y_{ID}), and the other part is used for energy harvesting (i.e. y_{EH}), which are given by:

$$y_{ID} \approx \sqrt{\rho_n} h_{sr}[n]x_s[n]+z_p, \tag{4}$$

$$y_{EH}=\sqrt{1-\rho_n} h_{sr}[n]x_s[n]+\sqrt{1-\rho_n} z_r[n], \tag{5}$$

Where $\rho_n \in [0,1]$ denotes the power splitting ratio [21] at time slot n, and $z_p \sim \mathcal{CN}(0,N_p)$ measures the processing noise which is modelled with AWGN. The approximation in (4) is due to the fact that the power of the processing noise is practically larger than the power of the channel noise. Hence, $\sqrt{\rho_n} z_r[n]$ is neglected. The harvested energy at time slot n is as follows:

$$E_{harv.}[n]:=\mathbb{E}\left(|y_{EH}(n)|^2\right)=(1-\rho_n)(p_s[n]h_{sr}^2[n]+N_r). \tag{6}$$

After decoding the information at the UAV, it re-encodes and transmits the signal to the destination in the next time slot. Therefore, the received signal at the destination is given by:

$$y_{des}[n] = h_{rd}[n]x_r[n] + z_d[n], \quad \text{for} \quad \text{n=1,2,...,N}, \tag{7}$$

Where x_r is the transmitted signal from UAV with $\mathbb{E}(|x_r[n]|^2) = p_r[n]$, and $z_d \sim \mathcal{CN}(0, N_d)$) is modelled with AWGN. Since the UAV has a pre-dedicated energy E_r, and also harvests energy over each time slot, the following inequalities, called the energy-causality constraint, are given:

$$\sum_{i=2}^{n} p_r[i] \le E_r + \sum_{i=1}^{n-1} E_{harv.}(n), \quad \text{for} \quad \text{n=2,...,N}. \tag{8}$$

3- Problem Statement

The main objective is to maximize the throughput (i.e., the sum-rate over N time slots data transmission) between the source and the destination. In this paper, the well-known decode-and-forward [20] strategy, where there is a data buffer in the UAV which can temporarily store the data before re-transmission to the destination, is used. Therefore, there is an information-causality constraint at the relay, which means the UAV can only forward the data that has been received previously. On the other hand, due to using power splitting technique at the UAV, we will have energy-causality constraints, meaning the UAV can only use the harvested energy which has been previously received from the source, and its initial energy.

Thus, at the time slot n, the following data rate at the UAV is achieved:

$$R_{sr}[n] = \log_2(1 + \rho_n p_s[n]\gamma_{sr}[n]), \; n = 1, ..., N-1, \tag{9}$$

Where $p_s[n]$ is the transmitted power of n-th slot at S, and γ_{sr} denotes the signal to noise ratio of the S-UAV links:

$$\gamma_{sr}[n] = \frac{\beta_0}{N_p(H^2 + x^2[n])} \tag{10}$$

It is worth mentioning that at the Nth time slot, the source does not transmit any data.

Similarly, the achievable data rate over the UAV and the destination link for slot n is given by:

$$R_{rd}[n] = \log_2(1 + p_r[n]\gamma_{rd}[n]), \; n = 2, ..., N, \tag{11}$$

Where $p_r[n]$ is the transmitted power at the UAV for time slot n, and γ_{rd} which is defined as follows, indicating the signal to noise ratio for UAV-D link.

$$\gamma_{rd}[n] = \frac{\beta_0}{N_d(H^2 + (D - x[n])^2)}, \tag{12}$$

Note that at time slot n=1, there is no data at the UAV to decode.

As demonstrated, the UAV can only transmit the data that has been received previously, hence the information-causality constraint is given by:

$$\sum_{i=2}^{n} R_{rd}[i] \le \sum_{i=1}^{n-1} R_{sr}[i] \quad n = 2, ..., N, \;\; R_{rd}[1] = R_{sr}[N] = 0. \tag{13}$$

To maximize the throughput provided energy and information-causality constraints, the following optimization problem can be formulated:

$$\text{(P1)}: \max_{\{p_s[n], p_r[n], \rho_n\}_{n=1}^{N}} \sum_{n=2}^{N} \log_2(1 + p_r[n]\gamma_{rd}[n]), \tag{14}$$

$$\text{s.t.:} \quad \sum_{n=1}^{N-1} p_s[n] \le E_s, \tag{15}$$

$$\sum_{i=2}^{n} p_r[i] \le E_r + \sum_{i=1}^{n-1} (1-\rho_i)(p_s[i]h_{sr}^2[i] + N_r)), \;\; n = 2, ..., N \tag{16}$$

$$\sum_{i=2}^{n} \log_2(1 + p_r[i]\gamma_{rd}[i]) \le \sum_{i=1}^{n-1} \log_2(1 + \rho_i p_s[i]\gamma_{sr}[i]), n = 2, ..., N \tag{17}$$

$$p_s[n] \ge 0, \;\; n = 1, ..., N-1 \tag{18}$$

$$p_r[n] \ge 0, \;\; n = 2, ..., N \tag{19}$$

$$0 \le \rho_n \le 1 \tag{20}$$

In (P1), (15) is due to the power constraint at S and the energy-causality constraint is given in (16). (17) indicates the information-causality constraint, and (18) and (19) guarantee the nonnegativity of powers, and (20) is the constraint on power splitting ratio. Due to (17), (P1) is a non-convex optimization problem, and it is difficult to be solved analytically. By introducing the slack variable $\{R_r[n]\}_{n=2}^{N}$, (P1) is reformulated as:

$$(\text{P2}): \max_{\{p_s[n], p_r[n], \rho_n, R_r[n]\}_{n=1}^{N}} \sum_{n=2}^{N} R_r[n], \tag{21}$$

$$\text{s.t.:} \quad R_r[n] \le \log_2(1 + p_r[n]\gamma_{rd}[n]), \ \ n = 2, \ldots, N \tag{22}$$

$$\sum_{n=1}^{N-1} p_s[n] \le E_s \tag{23}$$

$$\sum_{i=2}^{n} p_r[i] \le E_r + \sum_{i=1}^{n-1} (1-\rho_i)(p_s[i] h_{sr}^2[i] + N_r)), n = 2, \ldots, N \tag{24}$$

$$\sum_{i=2}^{n} R_r[i] \le \sum_{i=1}^{n-1} \log_2(1 + \rho_i p_s[i]\gamma_{sr}[i]), \ \ n = 2, \ldots, N \tag{25}$$

$$p_s[n] \ge 0 \ \ n = 1, \ldots, N-1 \tag{26}$$

$$p_r[n] \ge 0 \ \ n = 2, \ldots, N \tag{27}$$

$$0 \le \rho_n \le 1 \tag{28}$$

With respect to the power splitting ratio and the power allocations, this is a non-convex problem Therefore, we solve this problem by an iterative two-layer algorithm based on an inner and outer problem, which is presented in Algorithm 1. In the inner problem, we optimize power allocations for a fixed ρ. Therefore, the inner optimization problem is a convex, the results are derived in Theorem 1 and can also be efficiently computed by using the standard convex optimization techniques [22], or optimization software tools such as CVX [23]. Afterwards, in the outer problem for the fixed power allocations, it is clear that the optimization problem is a convex with respect to the splitting ratio, and the result are evaluated by using CVX tool. It is worth mentioning that as the maximum power and splitting ratio are non-negative and bounded, the feasible optimization set is closed. On the other hand, it is clear that the objective function is non-decreasing, and concave function and inner and outer problems are convex. Therefore, in each iteration the objective function of P2 is non-decreasing and the solution converges to a stationary point which is local optimum. To validate the convergence of the proposed solving method, Fig. 7 is presented in Section IV.

As demonstrated earlier, the Lagrangian is presented in Theorem. 1 to obtain the optimal power allocations of problem (P1) with fixed power splitting ratio.

Theorem 1: The optimal power allocations of problem (P1) are given by:

$$p_s^*[n] = \left[\frac{\sum_{i=n+1}^{N} \lambda_i}{\upsilon - \sum_{i=n+1}^{N} \alpha_i h_{sr}^2 (1-\rho_n)} - \frac{1}{\rho_n \gamma_{sr}[n]} \right]^+ \tag{29}$$

$$p_r^*[n] = \left[\frac{\beta_n}{\sum_{i=n}^{N} \alpha_i} - \frac{1}{\gamma_{rd}[n]} \right]^+ \tag{30}$$

Algorithm 1 Iterative power allocation and power splitting ratio optimization.

```
1: Initialize Power at source and the UAV, by allocating equal power to all slots.
2: Repeat
3: Fix the power allocation, find the optimal power splitting ratio for all slots, using CVX.
4: Fix the power splitting ratio, and update the optimal power allocation for all slots, using CVX until
       convergence or a maximum number of iterations has been reached.
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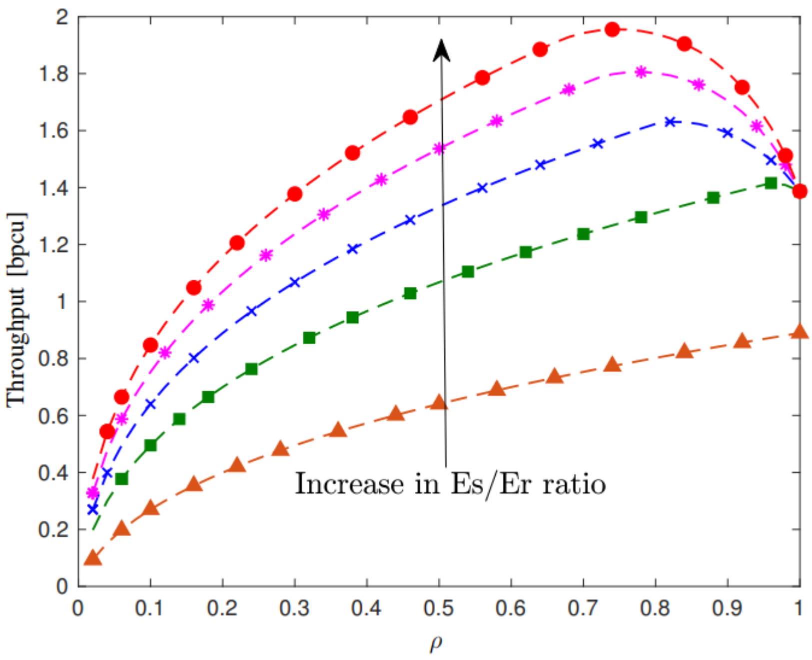

Fig. 3. Throughput versus different power splitting ratios, for N = 60 slots, Es = [25N, 75N, 125N, 175N], and Er = 15N.

$$R_r^*[n] = \left[\log_2\left(\frac{\beta_n \gamma_{rd}[n]}{\sum_{i=n}^{N} \alpha_i} \right) \right]^+ \tag{31}$$

Proof: By applying the Lagrangian of (P2), optimal solution of (P2) can be calculated. By letting λ_n, β_n, υ, and α_n as the Lagrange variables, the Lagrangian function of (P2) is written as:

$$\begin{aligned}\mathcal{L}(p_s[n], p_r[n], R_r[n], \lambda_n, \beta_n, \upsilon, \alpha_n) &= \sum_{n=2}^{N} R_r[n] \\ &+\sum_{n=2}^{N} \lambda_n \left[\sum_{i=1}^{n-1} \log_2(1+\rho_i p_s[i]\gamma_{sr}[i]) - \sum_{i=2}^{n} R_r[i] \right] \\ &+\sum_{n=2}^{N} \beta_n \left(\log_2(1+p_r[n]\gamma_{rd}[n]) - R_r[n] \right) + \upsilon(E_s - \sum_{n=1}^{N-1} p_s[n]) \\ &+\sum_{n=2}^{N} \alpha_n \left[\sum_{i=1}^{n-1} (1-\rho_i)(p_s(i)h_{sr}^2[i] + N_r) + E_r - \sum_{i=2}^{n} p_r[i] \right]\end{aligned} \tag{32}$$

By using the standard Lagrange method and the Karush-Kuhn-Tucker (KKT) conditions, the optimal solution of (32) can be calculated which are equal to zero according to the KKT conditions. Therefore, the optimal solution to (32) can be achieved by simplifying the equations (33–34) as follows:

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial p_s[n]} &= \sum_{i=n+1}^{N} \lambda_i \left[\frac{\rho_n \gamma_{sr}[n]}{1+\rho_n p_s[n]\gamma_{sr}[n]} \right] - \\ &\upsilon + \sum_{i=n+1}^{N} \alpha_i h_{sr}^2[n](1-\rho_n)\end{aligned} \tag{33}$$

$$\frac{\partial \mathcal{L}}{\partial p_r[n]} = \frac{\beta_n \gamma_{rd}[n]}{1+p_r[n]\gamma_{rd}[n]} - \sum_{i=n}^{N} \alpha_i \tag{34}$$

$$\frac{\partial \mathcal{L}}{\partial R_r[n]} = 1 - \beta_n - \sum_{i=n}^{N} \lambda_i \tag{35}$$

4- Numerical Results

In this section, numerical results are presented to characterize the performance of the proposed system. A mobile relaying cooperative system with S and D separated is assumed by D = 10, such that S and D are located at (0, 0, 0) and (10, 0, 0), respectively. The UAV files with a fixed unidirectional trajectory at the fixed altitude H = 1, above the source toward the destination, where it divides the distance to N equal slots. The UAV speed is fixed for each performance time T, where V = D/T and T = Nδ_t. In the following, β_0 = 1, N_r = N_d = 0.4, and N_p = 4 are used, unless specifically mentioned.

Fig. 3 depicts the throughput versus the power splitting ratio ρ_n for N = 60 time slots, and different ratios of $\frac{E_s}{E_r}$,

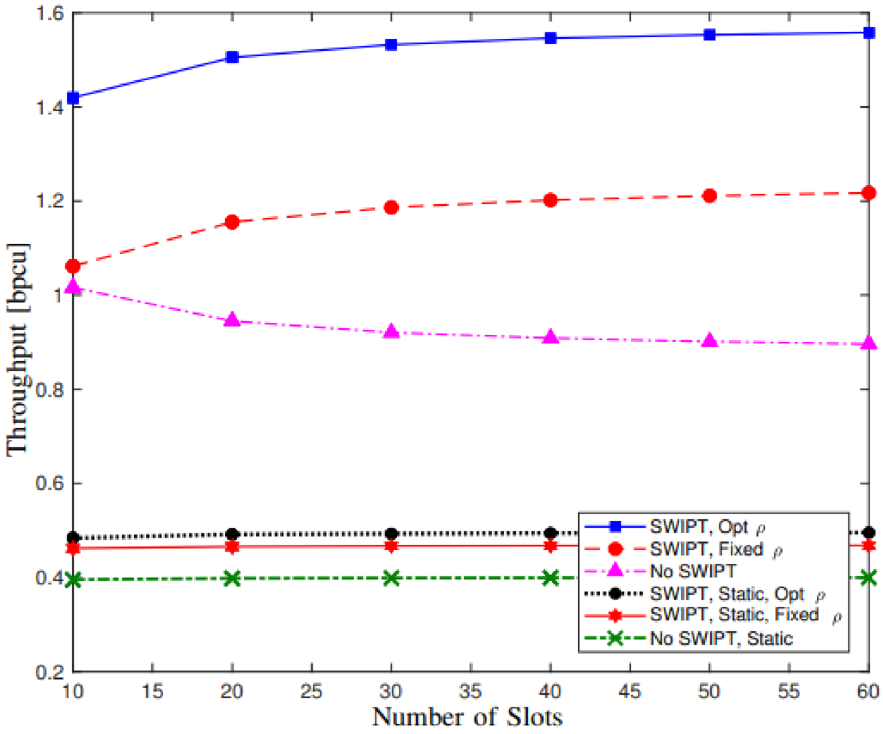

Fig. 4. Throughput versus number of slots for different scenarios, Es = 100N, Er = 5N.

with $E_s \in [25N, 75N, 125N, 175N]$, and $E_r = 15N$. It is worth mentioning that a fixed ρ_n is used for all time slots. It is observed that for small ratios of $\frac{E_s}{E_r}$, the throughput increases as ρ_n increases too, which implies that the power received from the source at the UAV is limited, and is better to decode the information at the UAV more precisely instead of charging the battery. In other words, the UAV has enough dedicated power compared to the source. In contrast, for higher ratios of $\frac{E_s}{E_r}$, an optimum value for ρ_n, exists, since increasing the harvesting energy reduces the quality of the signal for information decoding. Thus, there is a trade-off between harvesting the energy and the quality of the information decoding.

The comparison of throughput and different number of slots is illustrated in Fig.4 for mobile and fixed UAV with and without optimized SWIPT scheme (E_s = 100N and E_r = 5N). ρ_n is optimized for each time slot according to Algorithm (III) for the optimized power splitting ratio scenarios. It is shown that by utilizing the mobile UAV with optimized ρ_n, the throughput outperforms the mobile UAV with ρ_n = 0.5 and static[1] UAV with optimized ρ_n and ρ_n = 0.5, and UAV without SWIPT. Additionally, by increasing the number of time slots to more than 40, the performance improvement is negligible, meaning it is almost sufficient for UAV to send information to over 40 time slots instead of 60, hence cause less processing at UAV. Table 1 is also plotted to better illustrate the performance improvement between different models.

Energy efficiency versus spectral efficiency is plotted in Fig.5 for the mobile UAV with optimized power splitting and fixed ρ_n = 0.5. The energy efficiency of the system is defined as:

$$EE = \frac{\sum_{n=1}^{N-1} R_r[n]}{E_s / N}, \qquad (36)$$

and the spectral efficiency is given by:

$$SE = \frac{\sum_{n=1}^{N-1} R_r[n]}{N}. \qquad (37)$$

---

[1] Static UAV means that the location of UAV is fixed at (D/2 , 0, H).

Table 1. Throughput improvement for different models. Each percentage shows the increase in throughput with respect to the model below. In the last row," SWIPT, static, fixed ρn" is compared with" no SWIPT, static".

Model	Throughput Improvement
SWIPT, Opt ρ	30%
SWIPT, Fixed ρ	35%
No SWIPT	60%
SWIPT, Static, Opt ρ	10%
SWIPT, Static, Fixed ρ	25%

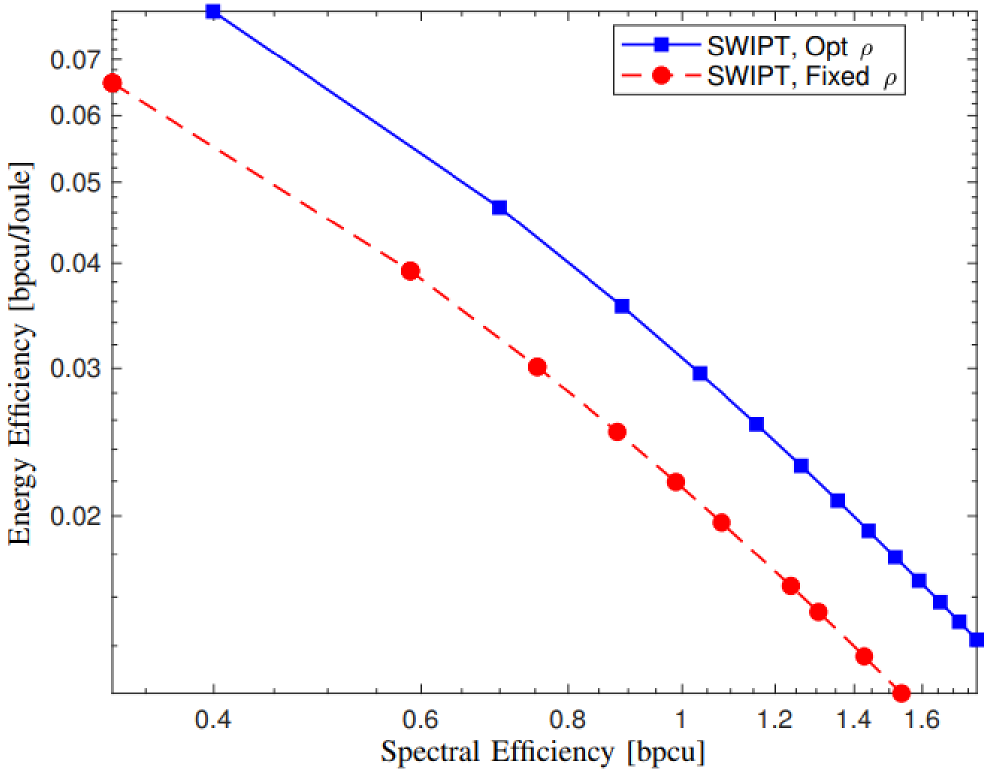

Fig. 5. Energy efficiency versus spectral efficiency, for Es from 5N to 125N, Er = 15N, and N=50.

Fig. 5. is depicted by driving the throughput for different values of E_s form 5N to 125N, with step size of 10N, and E_r = 15N. Afterwards calculating EE and SE from the equations (36) and (37). As expected, the energy efficiency is improved by 40% due to optimizing the power splitting ratio at the UAV.

In Fig. 6, the throughput versus $\frac{E_s}{E_r}$ is depicted for N = 50. As demonstrated earlier, as the processing noise is considered sufficiently larger than the channel noise, the cooperative transmission without utilizing SWIPT scheme has 50% to 0% better performance than the SWIPT for low values of $\frac{E_s}{E_r}$. However, the SWIPT scheme outperforms the non SWIPT up to 30% by increasing the $\frac{E_s}{E_r}$ ratio. In other words, SWIPT scheme is useful whenever the source has enough energy to share with the UAV.

Additionally, to validate the convergence of the proposed algorithm to the global optimal point, Fig. 7 is presented for N = 60, Es = 100N, Er = 5N. The figure confirms that the

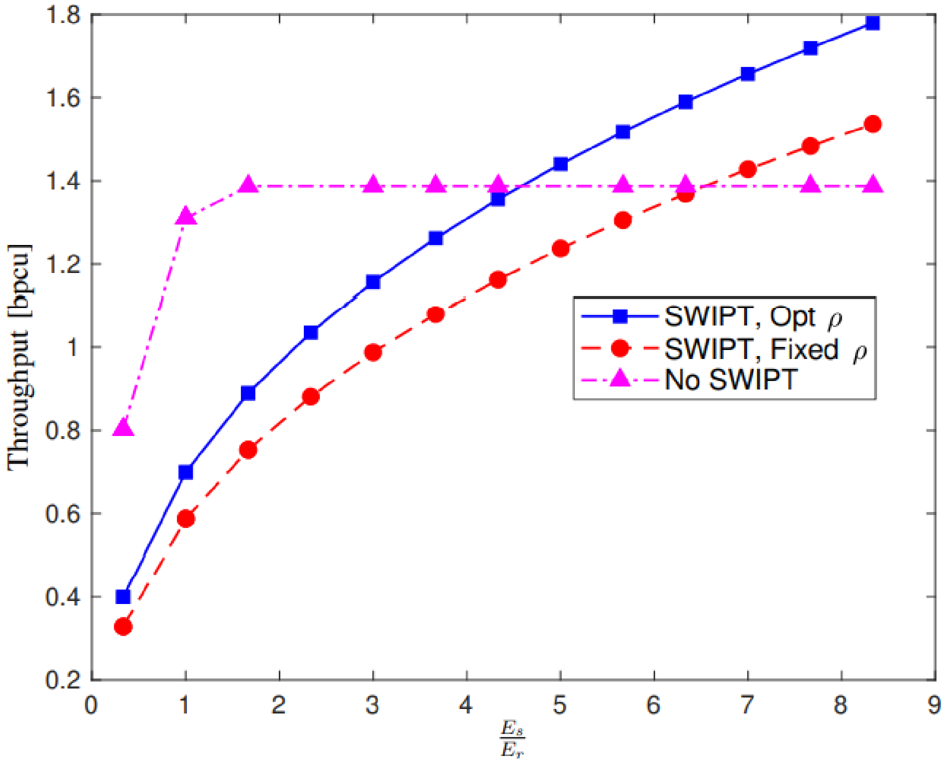

Fig. 6. Throughput versus different Es/Er ratios, for Es from 5N to 125N, Er = 15N, and N=50..

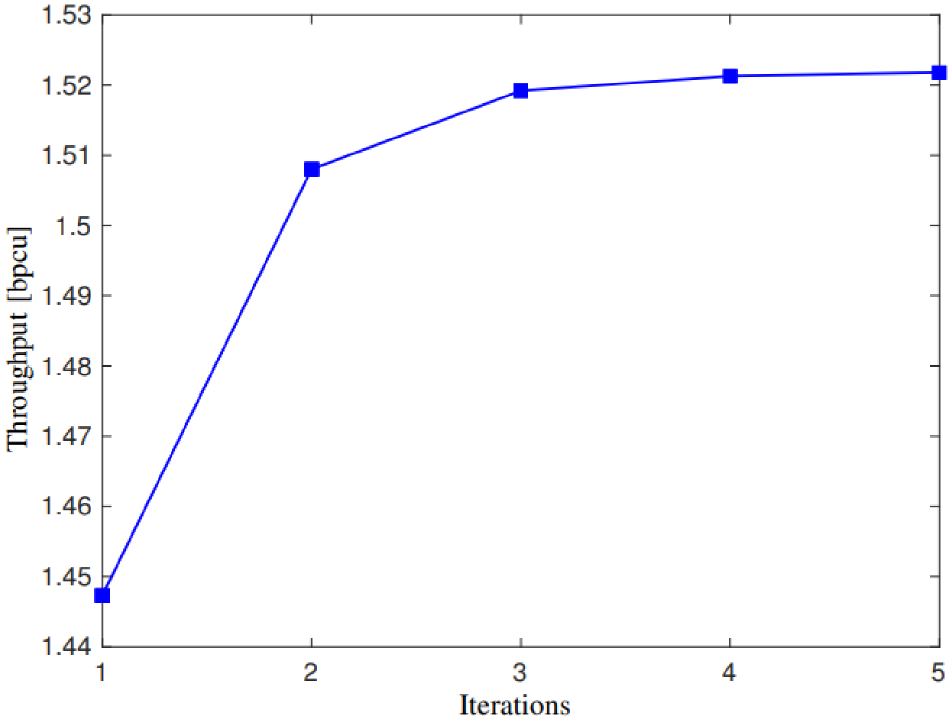

Fig. 7. Throughput versus iterations for N = 60, Es = 100N, Er = 5N, which shows the convergence of the proposed.

convergence achieves in a few numbers of iterations[1].

5- Conclusion

This paper studies a two-hop decode and forward SWIPT-based UAV cooperative communication between a source and a destination for multiple slots, with limited power at source and the UAV. The UAV can use the received energy from the source, not only for decoding the information, but also for harvesting energy and charging its battery by applying the power splitting technique. Afterwards, based on the state of its battery it retransmits the recovered messages to the destination. Since the transmission is performed over multiple time slots, sum-rate maximization in presence of energy-causality and information-causality constraints is analysed, and optimal resource allocations at the source, the UAV and optimal power splitting ratios over each slot are derived. Numerical results showed that compared to the conventional UAV-enabled mobile relaying systems and the static scenarios, a significant throughput gain is achieved using the proposed buffer-aided DF SWIPT UAV scheme. Hence, this method can be used to increase the throughput of UAV-enabled relay systems without increasing the weight and battery-capacity of the UAV.

References

[1] L. Gupta, R. Jain, and G. Vaszkun, “Survey of important issues in UAV communication networks,” IEEE Communications Surveys & Tutorials, vol. 18, no. 2, pp. 1123–1152, 2016.

[2] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, “A tutorial on UAVs for wireless networks: Applications, challenges, and open problems,” arXiv preprint arXiv:1803.00680, 2018.

[3] R. Austin, Unmanned aircraft systems: UAVs design, development and deployment, vol. 54. John Wiley & Sons, 2011.

[4] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, “3-D placement of an unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage,” IEEE Wireless Communications Letters, vol. 6, no. 4, pp. 434–437, 2017.

[5] J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, “Placement optimization of UAV-mounted mobile base stations,” IEEE Communications Letters, vol. 21, no. 3, pp. 604–607, 2017.

[6] J. Lyu, Y. Zeng, and R. Zhang, “Cyclical multiple access in UAV-aided communications: A throughput-delay trade-off,” IEEE Wireless Communications Letters, vol. 5, no. 6, pp. 600–603, 2016.

[7] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: Opportunities and challenges,” IEEE Communications Magazine, vol. 54, no. 5, pp. 36–42, 2016.

[8] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L. G. Giordano, A. Garcia-Rodriguez, and J. Yuan, “Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges,” IEEE Communications Surveys & Tutorials, 2019.

[9] Y. Zeng, R. Zhang, and T. J. Lim, “Throughput maximization for UAV-enabled mobile relaying systems,” IEEE Transactions on Communications, vol. 64, no. 12, pp. 4983–4996, 2016.

[10] X. Jiang, Z. Wu, Z. Yin, and Z. Yang, “Power and trajectory optimization for UAV-enabled amplify-and-forward relay networks,” IEEE Access, vol. 6, pp. 48688–48696, 2018.

[11] S. Hu, J. Flordelis, F. Rusek, and O. Edfors, “Unmanned aerial vehicle assisted cellular communication,” arXiv preprint arXiv:1803.05763, 2018.

[12] H. Shakhatreh, A. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani, “Unmanned aerial vehicles: A survey on civil applications and key research challenges,” arXiv preprint arXiv:1805.00881, 2018.

[13] S. Yin, J. Tan, and L. Li, “UAV-assisted cooperative communications with wireless information and power transfer,” arXiv preprint arXiv:1710.00174, 2017.

[14] S. Yin, Y. Zhao, and L. Li, “UAV-assisted cooperative communications with time-sharing SWIPT,” in 2018 IEEE International Conference on Communications (ICC), pp. 1–6, IEEE, 2018.

[15] Y. Zeng and R. Zhang, “Energy-efficient UAV communication with trajectory optimization,” IEEE Transactions on Wireless Communications, vol. 16, no. 6, pp. 3747–3760, 2017.

[16] J. Zhang, Y. Zeng, and R. Zhang, “Spectrum and energy efficiency maximization in UAV-enabled mobile relaying,” in 2017 IEEE International Conference on Communications (ICC), pp. 1–6, IEEE, 2017.

[17] Z. Yang, N. Huang, x. Hao, Y. Pan, Y. Li, and M. Chen, “Downlink resource allocation and power control for device-to device communication underlaying cellular networks,” IEEE Communications Letters, vol. 20, pp. 1–1, 05 2016.

[18] G. Zhang, Q. Wu, M. Cui, and R. Zhang, “Securing UAV communications via joint trajectory and power control,” IEEE Transactions on Wireless Communications, 2019.

[19] X. Hong, P. Liu, F. Zhou, S. Guo, and Z. Chu, “Resource allocation for secure UAV-assisted SWIPT systems,” IEEE Access, 2019.

[20] A. El Gamal and Y.-H. Kim, Network information theory. Cambridge university press, 2011.

[21] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, “Relaying protocols for wireless energy harvesting and information processing,” IEEE Transactions on Wireless Communications, vol. 12, no. 7, pp. 3622–3636, 2013.

[22] S. Boyd and L. Vandenberghe, Convex optimization. Cambridge university press, 2004. [23] M. Grant and S. Boyd, “CVX: Matlab software for disciplined convex programming, version 2.1,” 2014.

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[1] The simulations results are derived on a personal computer with an Intel core-i5 processor at 2.5 GHz, using 4 GB of RAM, and running CVX version 2.1. For this case with N = 60 and 5 iterations, the computations took 113 seconds.

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