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Abstract

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***Abstract*—For assisting data communications in human-unfriendly environments, Unmanned Aerial Vehicles (UAVs) are employed to relay data for ground sensors thanks to UAVs' flexible deployment, high mobility, and line-of-sight communications. In UAV relay networks, energy efficient data relay is critical due to limited battery of the ground sensing devices. In this paper, we propose a buffer-aware transmission scheduling optimization to minimize the energy consumption of the ground devices under constraints of buffer overflows and energy cost fairness on the ground devices. Moreover, we show that the problem is NP-complete and propose a heuristic algorithm to approximate the optimal scheduling solution in polynomial time. The performance of the proposed algorithm is evaluated in terms of network sizes, packet arrival rates, and fairness of the energy consumption. Numerical results confirm that the proposed scheduling algorithm reduces the energy consumption of the ground devices in a fair fashion, while the buffer overflow constraint holds.**

I. INTRODUCTION

Nowadays, Unmanned Aerial Vehicles (UAVs), also commonly known as drones, are developed to extend the coverage of a wireless network to areas in which there is a limited available infrastructure of wireless access points. Due to flexible deployment and high mobility, UAVs move sufficiently close to ground sensing devices, exploiting short-distance line-of-sight (LoS) communication links [1]. UAVs are utilized in many civilian and commercial applications, e.g., weather monitoring, traffic control and package delivery [2]. Moreover, UAVs are employed to relay data for the ground devices in harsh environment to a remote base station, such as environmental and natural disaster monitoring, border surveillance, emergency assistance, search and rescue missions in battlefield [3]. In such harsh environments, conventional terrestrial communication networks requiring persistent power supplies are unreliable [4].

Having a ground device transmit data during instances when the channel quality is poor is likely to result in packet reception errors, which in turn would require retransmissions and thus increased energy expenditure. Since the ground device is severely restrained by battery power, it is critical to schedule data transmissions of the ground devices in an energy efficient manner. Moreover, the ground devices undergo random data arrivals, and buffer the data to be transmitted to the UAV. The buffers are finite, and the new data arrivals have to be dropped if the buffers are full and start overflowing. In addition, the energy consumption of the ground devices needs to be balanced. Otherwise, some ground devices, that experience poor channels to the UAV, would run out of energy sooner than the others. This results in coverage holes in the ground sensing network.

In this paper, a buffer-aware transmission scheduling optimization is first formulated to minimize the energy consumption of the ground devices, while ensuring a fair energy cost in the network. We first show that the optimization problem is NP-complete. Next, we propose a suboptimal heuristic algorithm, named Energy Efficient, Fair and Buffer-aware Scheduling (EEFBS), to minimize the energy consumption of the ground devices in polynomial time. Specifically, the EEFBS algorithm prioritizes data transmissions of the ground devices based on link quality and energy consumption. EEFBS schedules the ground device with the lowest energy consumption and the highest Signal-to-Noise Ratio(SNR) to transmit their data first. In particular, for the ground devices with the same energy consumption, EEFBS schedules the device with the best link quality, in order to reduce the energy consumption on the packet retransmissions of the ground devices.

Moreover, we conduct extensive simulations to evaluate performance of the proposed EEFBS algorithm in term of network sizes, packet arrival rates, and impact of the energy fairness. The numerical results show that EEFBS outperforms the existing greedy scheduling algorithms with substantial gains about 40%. The results also show that the energy consumption of the ground devices drops 17% with the downgrade of the energy fairness requirement.

The rest of this paper is organized as follows. Section II presents related work on UAV-assisted mobile networks. Section III studies the system model. In Section IV, the optimization problem is formulated to minimize the energy consumption of the ground devices. Section V investigates the EEFBS heuristic algorithm. The performance of EEFBS is evaluated in Section VI, and Section VII concludes this paper.

II. RELATED WORK

In this section, we review the literature on the UAV-assisted mobile networks.

A user scheduling scheme is studied to improve throughput and fairness in the UAV relay network [5], where the ground users transmit data in non-orthogonal channels. In [6], the trajectory planning of the UAV and transmit power allocation are developed to improve the network throughput in the UAV relay network. A resource management scheme is studied to schedule the data transmission of the ground users and the transmit power of the UAV to improve network throughput of the UAV relay network [7]. A UAV-assisted mobile edge computing architecture is studied in [8], where the UAV collects or relays data of the ground users as either a data sink or a data relay. The UAV can share the computing tasks that are allocated to the ground users while offloading the tasks to a remote data center. Given a circular flight trajectory of the UAV, a communication protocol is presented to adjust the data rate according to the UAV's locations to reduce the outage probability of the UAV [9]. In [10] and [11], a security scheme is studied to maximize the worst-case secrecy rate among the users by planning the UAV trajectories and scheduling the data transmission. The UAVs relay data for the ground users while jamming the eavesdroppers to improve communication security. The legitimate UAV utilizes an energy-efficient jamming strategy in [12] to maximize the amount of eavesdropped packets. Moreover, the legitimate UAV monitors the suspicious flight according to tracking algorithm. In [13], the legitimate UAV surveillance is studied, where the legitimate UAV tracks the suspicious UAVs via eavesdropping for preventing terror attacks. In [14], the jamming power is allocated using a polynomially solvable optimization to maximize the eavesdropping rate at the legitimate UAV. To simplify the legitimate eavesdropping and jamming, a power-efficient legitimate eavesdropping algorithm is developed. [15] theoretically studies a low-power eavesdropping and jamming selection policy for the legitimate UAVs over fading channel.

III. System Model

In this section, we present the data relay model of the UAV, and the energy and queuing model of the ground devices.

A. Data Relay Model

Consider N ground devices in the network. Figure 1 depicts geometrical coordinates of the ground devices, the UAV and the base station. A base station locates at (0, 0, 0), and the location of ground device i is $w_i = (x_i, y_i, 0)$, $i \in [1, N]$. The altitude of the UAV's flight is maintained at h. At time t, the location of the UAV along its flight trajectory is (x(t), y(t), h) where $0 \leq t \leq T$ and T is flight duration of the UAV. The distance between device i and the UAV at t can be given by

$$d_i(t) = \sqrt{(x(t) - x_i)^2 + (y(t) - y_i)^2 + h^2)} \tag{1}$$

The SNR of the link between device i and the UAV at time slot t is denoted by $\gamma_i(t)$, which is

$$\gamma_i(t) = \sqrt{\frac{\lambda H_i(t-1) + n\sqrt{1-\lambda^2} k_2^{-1} \ln \frac{k_1}{\epsilon}(R_i^{tx}(t) - 1)}{N_0 d_i^{\alpha_1}(t)}} \tag{2}$$

where N_0 is the noise power, ϵ is the required instantaneous bit error rate, and n is a Gaussian random number generated by AWGN. α_1 is the path-loss exponent. $H_i(t)$ is channel gain

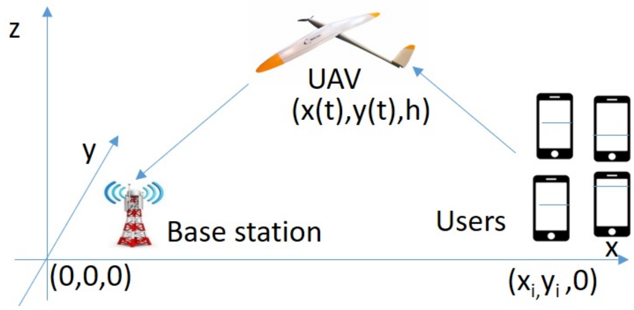

Fig. 1. A UAV-assisted mobile relaying system

of the link between device i and the UAV. $R_i^{tx}(t)$ is the data rate of device i. k_1 and k_2 are positive fixed constants relating to the channel.

B. Energy Model

The energy consumption of data transmission of device i at t is $E_i^{tx}(t)$ ($i \in [1, N]$), which can be given by

$$E_i^{tx}(t) = P_i^{tx}(t) \frac{L}{R_i^{tx}(t)}, \tag{3}$$

where L is the data packet length. Moreover, the achievable rate of device i at t is [16]

$$R_i^{tx}(t) = (1 + \frac{P_i^{tx}(t)}{\delta_i(t)}) \tag{4}$$

where $\delta_i(t) = \frac{\ln(\frac{k_1}{\epsilon})}{k_2 \gamma_i(t)}$. Based on (4), the transmit power of device i can be

$$P_i^{tx}(t) = \delta_i(t)(R_i^{tx}(t) - 1). \tag{5}$$

By substituting (5) to (3), the energy consumption of device i can be presented as

$$E_i^{tx}(t) = L\delta_i(t)(1 - \frac{1}{R_i^{tx}(t)}). \tag{6}$$

C. Queuing Model

Let $A_i(t)$ denote the number of data packets arriving at device i for transmission at time t. $U_i(t)$ is the current buffer length of i and $R_i^{tx}(t)$ is the number of bits transmitted to the UAV. Therefore the queueing system of the ground device can be formulated by

$$U_i(t) = max[U_i(t-1) + A_i(t) - R_i^{tx}(t), 0] \tag{7}$$

According to (7), the queuing model of the ground device prevents $U_i(t) < 0$ when the number of transmitted data packets is larger than the number of packets in the buffer. Furthermore, the buffer overflow probability of device i is denoted by J_i, which is

$$J_i = \frac{1}{T} \Sigma_{t=1}^{T} I\{U_i(t) > M\} \tag{8}$$

where I{} is an indicator function. If the length of the queue is greater than the maximum queue length M, $I\{....\} = 1$, which indicates buffer overflows at device i. Otherwise, the indicator function is equal to zero.

IV. Problem Formulation

We define x_i^t as a binary indicator of device i being scheduled for data transmission at time t. If device i is scheduled by the UAV at t, $x_i^t = 1$; otherwise, $x_i^t = 0$. The scheduling optimization of data transmission in UAV relay networks is formulated as *JPF*. The objective is to minimize energy consumption of all the ground devices. The optimization comprises three constraints;$J_i = 0$ is the constraint for managing buffer overflow. $P_i^{tx}(t)x_i^t \leq P_{max}$ ensures that the transmit power of the scheduled ground device does not exceed the maximum transmit power P_{max}. $E_i^{tx}x_i^t \leq \rho.E_0$ is the fairness constraint on the energy consumption, where E_0 is the initial energy of the ground device and $\rho(\in (0,1])$ is a fairness coefficient which controls the level of fairness in the proposed scheduling. This constraint balances the energy consumption of the ground devices, which prevents energy holes.
JPF:

$$\text{Minimize:}\Sigma_{i=1}^{N}\Sigma_{t=1}^{T}E_i^{tx}(t)x_i^t \tag{9}$$

Subject to:

$$J_i = 0 \tag{10}$$

$$P_i^{tx}(t)x_i^t \leq P_{max} \tag{11}$$

$$E_i^{tx}x_i^t \leq \rho.E_0 \tag{12}$$

V. EEFBS Heuristic Algorithm

Minimizing the energy consumption in the problem(JPF) is a typical Multiple Knapsack Problem (MKP). We reduce an instance of MKP to our scheduling problem by considering the capacity of knapsack as maximum energy consumption. The items to be put in knapsacks are energy consumed by each ground device with the size of E_i^{tx}. The parameters of the buffer overflow and energy fairness are satisfied by any placement of items. For example, for overflow the amount of energy consumed by the ground device(i.e., the items) should not be greater than capacity. In this way, the optimal placement of the items in knapsacks is reduced to such an instance of our scheduling problem. Since the optimal placements of items in knapsacks is an NP problem, this shows that our scheduling problem is NP-complete. Furthermore, we propose EEFBS to approximate the optimal solution of optimization. The EEFBS schedules the ground devices based on both the link quality and real-time energy consumption of the ground devices, where a ratio of $\frac{\gamma_i}{E_i^{tx}}$ is defined for the ground devices. A scheduling priority list is created in EEFBS, where the length is np, which includes np ground devices with top value of $\frac{\gamma_i}{E_i^{tx}}$.

Algorithm 1 EEFBS

while *iterations* $\leq N_{rounds}$ **do**
  The UAV calculates the ratio $\frac{\gamma_i}{E_i^{tx}}$ for each ground device i.
  The UAV sorts the ground devices by $\frac{\gamma_i}{E_i^{tx}}$ in an descending order.
  The UAV creates a priority list and includes np ground devices with highest $\frac{\gamma_i}{E_i^{tx}}$ in this list.
  for *each user i in the priority list* **do**
    if $J(i) = 1$ *and* $P_i \leq P_{max}$ *and* $E_i^{tx} \leq \rho.E_0$ **then**
      The UAV schedules ground device i to transmit.
    else
      i=i+1
    end
  end
  iterations=iterations+1
end

In EEFBS, $\frac{\gamma_i}{E_i^{tx}}$ that is derived for each of the ground devices are sorted in a descending order. Then, the scheduling priority list is created. Next, each ground device of the priority list is checked against overflow, power and fairness constraints, if ground device satisfied the constraint it scheduled for the transmission otherwise chance is given to the next ground device of the priority list.

VI. Performance Evaluation

In this section, we present the simulations prototyping our proposed scheduling. Numerical results are shown with regards to the energy consumption of the ground devices. Table I shows simulation parameters.

TABLE I
Simulation Parameters

Parameters	Values
ϵ	0.05
k_1	0.2
k_2	3
P_{max}	5
E_0	5
N_{rounds}	20
r	40
N_{users}	40
ρ	0.8

A. Simulation configuration

The performance of the proposed EEFBS is evaluated based on MATLAB. The simulations are conducted on a 2.7 GHz Intel core i5 processor with 8 GB of memory. Figure 2 shows simulation environment. It comprises, the UAV flies along a circular trajectory which contains a sequence of waypoints, and sensor nodes are randomly deployed on the ground.

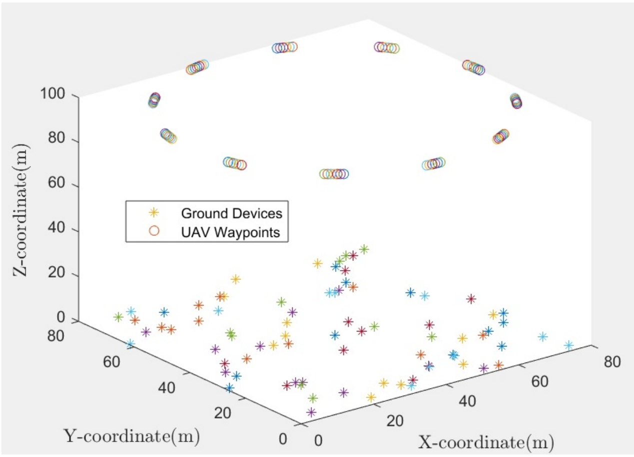

Fig. 2. Simulation Environment

Our network for scheduling contains one UAV and the number of users is 40 with initial energy equal to 5 joules. A circular flight trajectory with radius of r=40 is considered. The users are randomly distributed on the ground. For comparison purposes, we simulate two other scheduling algorithms that are suitable in our context setting. The first algorithm is a greedy algorithm, where the scheduling is based on the data queue length of ground devices. The device with full buffer has a higher priority to transmit data. The second strategy is a random scheduling algorithm, where the ground devices transmit data in a random-contention fashion. Moreover, the performance of the EEFBS is shown according to the number of ground devices, packet arrival rate (PAR) at the ground device, the simulation time step, and the ρ.

B. Results analysis

Figure 3 shows the energy consumption of the ground devices with an increasing network size, where EEFBS-0.5 is our heuristic algorithm with $\rho = 0.5$, and EEFBS-0.2 is our heuristic with $\rho = 0.2$. The EEFBS-0.2 has the best performance which proves the effectiveness of our approach while the random scheduling scheme has the worst performance. The EEFBS-0.2 outperforms the random scheduling and greedy algorithm with substantial gains about 40 and 20 percent, respectively. And the gains keep growing with the number of ground devices. Moreover, we observe that the ρ effects the performance of the proposed EEFBS algorithm. The energy consumption of the ground devices drops from 79 percent to 62 percent, when the ρ decreases from 0.5 to 0.2. Figure 4 shows the energy consumption of the ground devices with regards to the ρ ,where ρ is set to 0.2, 0.4, 0.6, or 0.8. According to this figure, when ρ is 0.8, the highest amount of energy is consumed, and as ρ decreases the energy consumption proportionally decreases. In the first 6 rounds, the energy consumption of the ground devices is not effected by the ρ . However, since round 7, EEFBS with $\rho = 0.2$ outperforms the others and achieves the lowest energy consumption. In particular, at round 20, EEFBS with $\rho = 0.2$ has 28 percent lower energy consumption than EEFBS with $\rho = 0.8$. This is due to the key effect of ρ, according to ρ constraint as we increase the ρ higher share of energy is consumed.

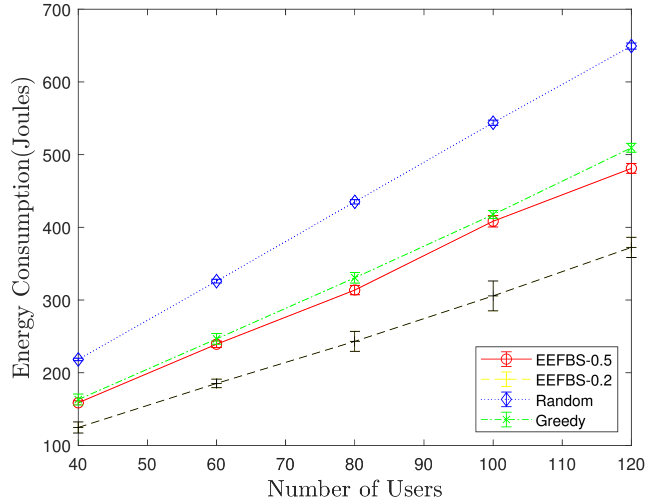

Fig. 3. Comparing energy consumption of EEFBS with random and greedy scheduling. The errors bars show 95% confidence interval.

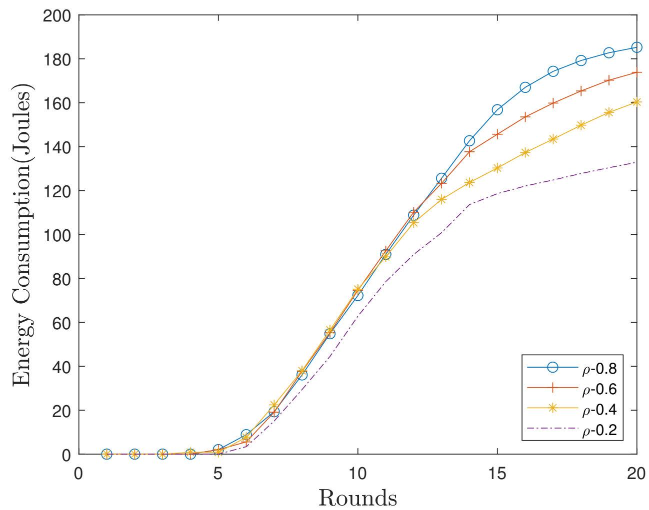

Fig. 4. Comparing energy consumption of users by varying ρ

Given $N = 40$ or 60, Figure 5 demonstrates how the proposed EEFBS algorithm is effected by the ρ, where the errors bars show 95% confidence interval. In case of $N = 40$, when ρ is 0.1, energy consumption is 41 percent and by increasing it energy consumption reaches to 80 percent and finally leveled off at 96 percent. The trend for energy consumption for $N = 60$ by varying ρ is similar to that of $N = 40$. In other word, increasing the number of users does not have any percentage grows. The reason is that fairness constraint is independent of the number of users and increasing it does not result in percentage gain.

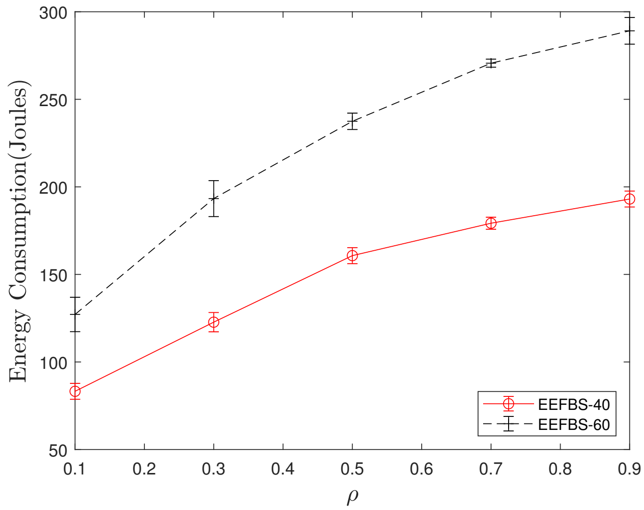

Fig. 5. Energy consumption of the ground devices with regards to the ρ . The errors bars show 95% confidence interval.

Figure 6 shows the performance achieved by EEFBS with respect to the packet arrival rate. Generally, the energy consumption of the ground devices increases with the growth of PAR. The reason is that a high PAR leads to more buffer overflows at the devices.

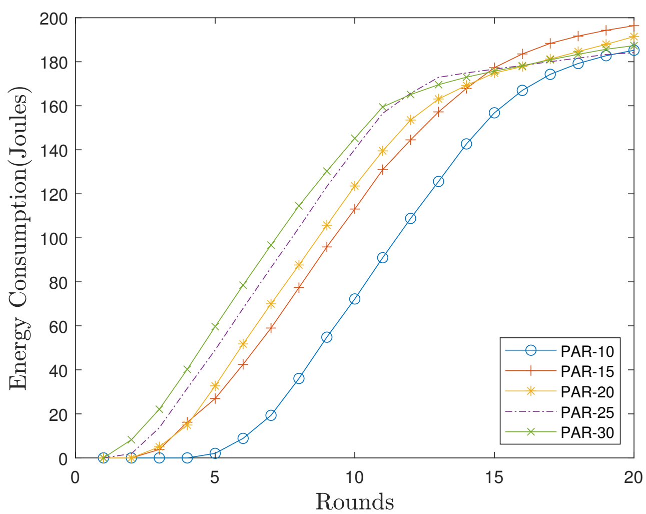

Fig. 6. The effect of packet arrival rate on the energy consumption of the ground devices.

Figure 7 demonstrates the performance of EEFBS according to the time steps, where $N = 40$, $\rho = 0.8$, and the initial energy of the battery is set to 5, 15, or 20 Joules. Particularly, at the first 5 rounds, the energy consumption is zero, namely, none of the ground devices is scheduled. Because no overflow happens in initial steps. From round 6 to 20, by coming more packets, overflow start happening and nodes are scheduled, hence energy consumption is initiated until energy consumption level off at 180 joules when initial energy is 5. For the other two curves initial energy is 15 and 20, they not reach to convergence due to higher amount of initial energy and hence need more rounds to converge.

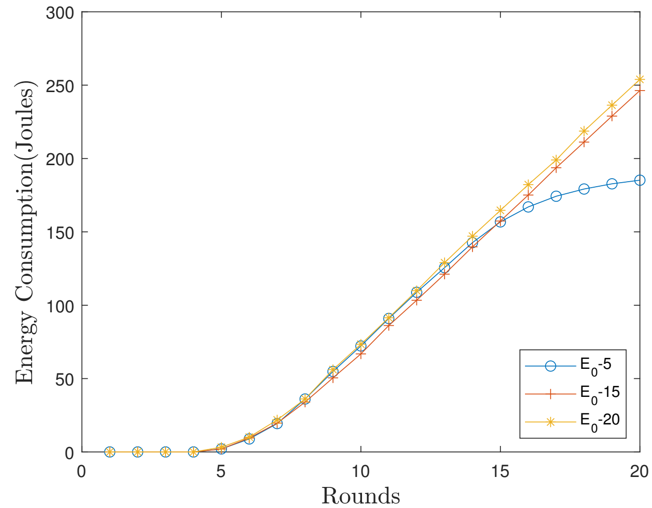

Fig. 7. Energy consumption of users for different initial values of energy.

VII. Conclusion

In this paper, we proposed an energy efficient and buffer-aware scheduling scheme for UAV-aided relaying. We investigated the problem to minimize energy consumption of users by optimizing user selection, subject to overflow, power and fairness constraint. We proposed an effective heuristic to solve the formulated problem. We conducted performance evaluation in MATLAB and compared the performance of our heuristic with a random and a greedy benchmark. We mainly compared them from energy consumption point of view for different scenarios, results confirm that the proposed approach outperforms two benchmarks, random and greedy. We plan to consider mobility for users and solve the problem using deep reinforcement learning.

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