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ENERGY HARVESTING EFFICIENCY FOR IRS-ENABLED UAV-COMMUNICATION

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ABSTRACT

With the increased use of smart devices, new technologies and designs are being incorporated into next-generation cellular networks using unmanned aerial vehicle (UAV) as aerial base stations and Intelligent Reflecting Surfaces (IRSs) to enhance coverage, capacity, reliability, and energy efficiency of these wireless networks. However, most of the UAV communication systems suffer from high energy consumption, which limits the flying time of UAVs. We can harvest energy from dedicated RF sources or signals in the surrounding environment for UAVs because it offers the potential to increase their range and endurance. This paper discusses the efficiency of energy harvesting for both terrestrial and aerial IRSs in future wireless networks to reap the benefits of smart reflections in three-dimensional (3D) space UAV communication network.

Keywords: UAV Communications, Energy Harvesting, Reconfigurable Intelligent Surface, Intelligent Reflecting Surface.

I. INTRODUCTION

1.1 Rising Demand for 5G

The need for high-speed wireless access has been incessantly growing, fuelled by the rapid proliferation of highly capable mobile devices such as smartphones, tablets, and more recently drone-UEs and IoT-style gadgets. 5G is based on OFDM (Orthogonal frequency-division multiplexing), a method of modulating a digital signal across several different channels to reduce interference. 5G wider bandwidth technologies such as sub-6 GHz and millimeter wave (mmW) and beamforming. Like 4G LTE, 5G OFDM operates based on the same mobile networking principles. 5G can operate in both lower bands (e.g., sub-6 GHz) as well as mmW (e.g., 24 GHz and up), which will bring extreme capacity, multi-Gbps throughput, and low latency. 5G is designed to not only deliver faster, better mobile broadband services compared to 4G LTE, but can also expand into new service areas such as mission-critical communications and connecting the massive IoT.

Specifications	4G	5G
Full form	Fourth Generation	Fifth Generation
Data Bandwidth	2Mbps to 1Gbps	1Gbps and higher as per need
Frequency Band	2 to 8 GHz	3 to 300 GHz
standards	AI access convergence including OFDMA,MC-CDMA,network-LMPS	CDMA and BDMA
technologies	unified IP, seamless integration of broadband LAN/WAN/PAN and WLAN	Unified IP, seamless integration of broadband LAN/WAN/PAN/WLAN and advanced technologies based on OFDM modulation used in 5G
service	Dynamic information access, wearable devices, HD streaming, global roaming	Dynamic information access, werable devices, HD streaming, any demand of users
Multiple Access	CDMA	CDMA,BDMA
Core network	All IP network	Flatter IP network, 5G network interfacing(5G-NI)
Handoff	Horizontal and vertical	Horizontal and vertical
Initiation from	year-2010	year-2015

Fig 1: Comparison between 4G and 5G

To achieve faster speeds, lower latency, extremely high reliability and more ambitious network performance in 5G communication and support advanced technologies like AR (Augmented Reality) and VR (Virtual Reality) may not be fully be achieved using the current technologies. A rudimentary challenge lies within the random and time-varying wireless channels. Notable efforts have been devoted to solving this challenge by e.g., employing efficient modulation and coding schemes as well as various space-time-frequency diversity techniques to compensate for the channel shadowing/fading, or implementing channel-based dynamic power/rate control and beamforming to adapt to the channel conditions. Nonetheless, these techniques were unable to alter the wireless channel itself, which prompted the new concept of a controllable/reconfigurable environment for wireless communications.

1.2 UAV-based approach

This can be achieved by two main approaches that have been extensively researched in recent years, namely, unmanned aerial vehicle (UAV)-assisted communication [1], [2] and intelligent reflecting surface (IRS)-aided communication [3]. An IRS is described as a planar surface which consists of multiple passive elements, where each element has the ability to independently shift the phase of the electromagnetic waves impinging on itself.

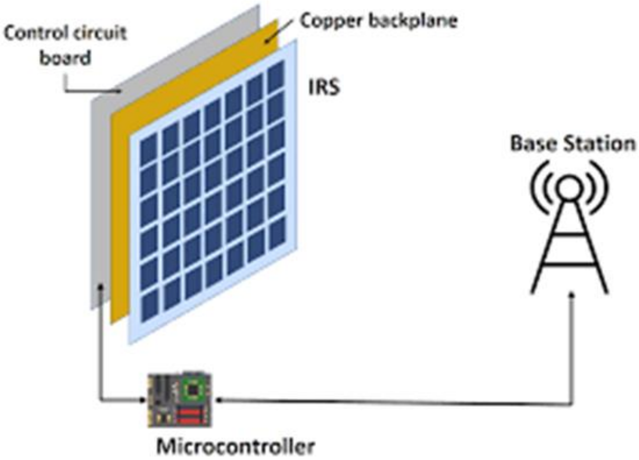


Fig 2: Architecture of an IRS.

The IRS can enhance the signal gain for a desired location, resulting in a virtual line-of-sight (LoS) path. Hence, it can function as a controllable relay with minimal power consumption. We can combine UAV communication systems with IRSs, to reap the benefits of both technologies. The outage probability, ergodic capacity, and energy efficiency of wireless communication systems supported by the IRS equipped UAVs was analyzed in [4].

1.3 UAV Constraints

UAVs, however usually have stringent size, weight, and power (SWAP) constraints [8], which impose critical limits on their flight time or endurance, and hence communication performance. Specifically, besides the transceiver power consumption, UAVs need to spend additional propulsion energy to remain airborne and support high mobility over the air, which is usually several orders-of-magnitude higher than their communication energy. We can't keep increasing the size of the on-board battery hence, other energy sources need to be discovered.

Recently, energy harvesting [40]–[41][42][43][44] has received a great deal of attention in prolonging the lifetime of low-power devices. Different from conventional wireless powered communication network (WPCN), UAV-enabled WPCN can exploit the mobility of UAVs to further improve the system performance. Energy harvesting is the process by which energy is derived from external sources, captured, and stored for small, wireless autonomous devices. Since the UAV will be employed in a RF system environment, we can harvest energy from neighbouring RF devices.

The aim of this research is to analyze the efficiency of energy harvesting in an IRS- enabled UAV communication system.

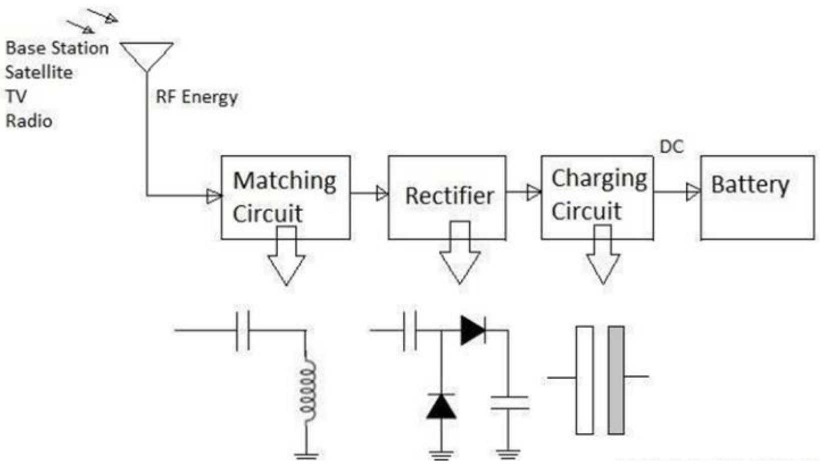
1. Calculate the power consumption of a UAV in-flight.
2. Calculate the average power harvested at a certain distance.
3. Calculate the efficiency.

II. METHODOLOGY

2.1 RF Energy Harvesting

An RF energy harvesting circuit usually consists of an antenna, an impedance matching circuit, a rectifier, a voltage multiplier, and an energy storage device or load. In an RF energy harvesting system, first, the transmitted RF signal propagating through wireless transmission medium is captured by a single antenna or multiple antennas in the far-field region. The impedance matching circuit is used to provide the maximum power transfer. Then, the rectifier converts RF power in direct current (DC). The output voltage of the rectifier is usually very low to drive a wireless device. Therefore, a voltage multiplier is used to increase the DC voltage level. Radio-frequency (RF) energy can be collected from the environment, called ambient RF energy harvesting (RF-EH) which considered as free powering sources. Finally, the harvested energy can be stored into an energy storage device, such as a rechargeable battery.

A RF energy harvesting system is described as follows.



The system model considered for this report is described as follows. Assume that there is one rotary UAV, K IRSs mounted on K buildings respectively and N UEs to be served, as shown in Fig. 3. We assume that the UAV serves all the UEs via the downlink transmission system. Also, assume that the UEs are located in the crowded area where they suffer from severe path loss and high attenuation, caused by tall buildings and trees. IRSs are deployed for enhancing the communication quality of UEs.

The UAV flies at a fixed altitude H^U (in meters) over a rectangle target area with side lengths [X_{max} , Y_{max}] for a certain period of time T_{all}. We denote the set of IRSs as K, {k = 1, 2, ..., K} and the set of UEs as N, {n = 1, 2, ..., N}. For simplicity, we divide T_{all} into T time slots (TSs), each of which has the maximal time duration T_d . Also, the set of TSs is denoted as T, {1, 2, ...T }.

Additionally, each IRS is equipped with a uniform linear array (ULA) with M reflecting elements, which could boost the useful signal power by adjusting the phase shifts of the reflecting elements. As a result, the set of reflecting elements of IRS k is denoted as M_k , {1, 2, ..., M}.

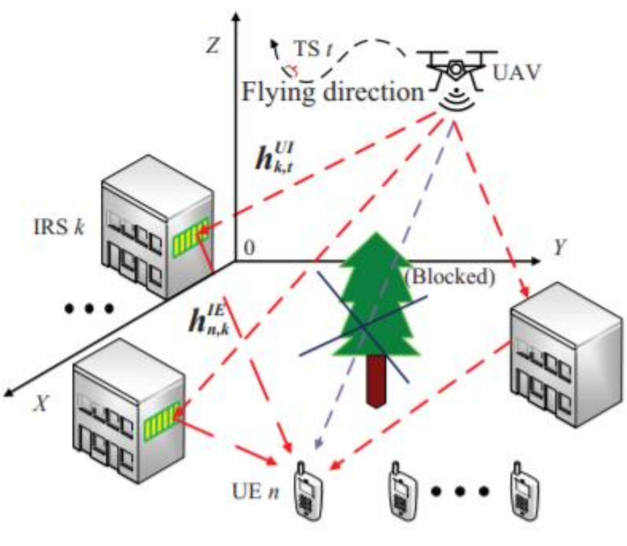


Fig 3: Architecture of IRS-aided UAV communication system.

The coordinate of IRS k as [XI k , Y I k , HI k], the coordinate of UE n as [x_n, y_n]. Thus, the distance between UAV and IRS k in TS t is expressed as

$$d_{k,t}^{UI} = \sqrt{\left(X_t^U - X_k^I\right)^2 + \left(Y_t^U - Y_k^I\right)^2 + \left(H^U - H_k^I\right)^2}.$$

Similarly, the distance between IRS k and UE n is given by

$$d_{n,k}^{IE} = \sqrt{\left(X_k^I - x_n\right)^2 + \left(Y_k^I - y_n\right)^2 + \left(H_k^I\right)^2}.$$

The height of UAVs is denoted by H. Note that UAVs can be used to offload traffic from the ground cellular BSs and reduce congestion around hotspots. In energy harvesting applications, UAVs can be used to transfer energy to e.g., ground sensors and low-power IoT devices, to energize them. They can also be deployed in case of emergencies during which ground infrastructure is strained [18]. In our model, the UEs are clustered around the projections of UAVs on the ground, and the locations of the clustered UEs is described by a PCP, denoted by Φ_C. In applications involving UAVs, UEs are expected to be located in high UE density areas, forming clusters.

2.2 Pathloss calculation

As mentioned in [16], the calculation of FSPL is very important for calculating the energy harvesting efficiency. We assume LoS communication is ensured for both the UAV-IRS and IRS-UE links. As a result, the path loss from a typical UE to a 0^{th} tier UAV can be formulated as

$$\boldsymbol{h}_{k,t}^{UI} = \sqrt{\frac{\alpha}{(d_{k,t}^{UI})^2}}\left[1, e^{-j\frac{2\pi}{\lambda}d\phi_{k,t}^{UI}}, ..., e^{-j\frac{2\pi}{\lambda}(M-1)d\phi_{k,t}^{UI}}\right]^T$$

Applying the formula,

$$P_L(dB) = 20\log_{10}(f) + 20\log_{10}(R) + 20\log_{10}(\frac{4\pi}{c}) - G_T - G_R$$

mentioned in [15], we can plot the FSPL for a communication system at a given frequency.

The pathloss calculated from the channel gain for a 30GHz communication is plotted as follows.

2.3 Energy consumption calculation

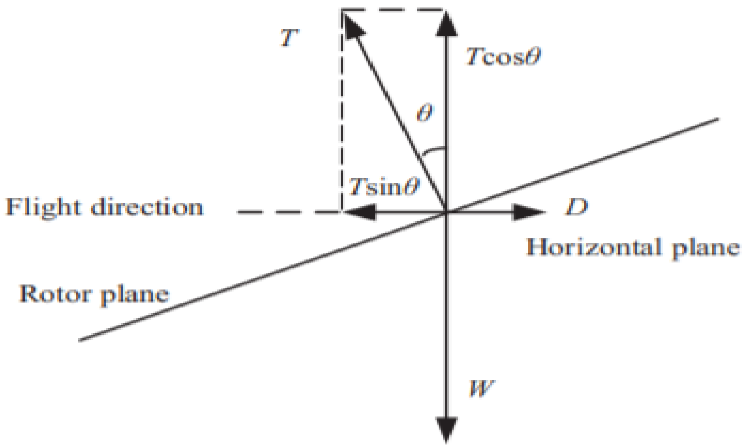


Fig 4: Schematic of the forces on a UAV with a fixed height

We first obtain the propulsion energy consumption model with a fixed height and straight flight. Fig.4 shows the simplified schematics of the longitudinal forces acting on the aircraft with fixed a height, which include the following forces: (i) T: rotor thrust, normal to the disc plane and directed upward; (ii) D: fuselage drag, which is in the opposite direction of the aircraft velocity; and (iii) W: aircraft weight. In Fig.13, θ is the tilt angle of the rotor disc. From Fig.13, we have the following equation:

$$T \sin\theta - D = ma, W - T\cos\theta = 0,$$

where a denotes the acceleration. According to [20, Eq. (4.5)], the UAV fuselage drag D can be written as:

$$D = 1/2\ \rho S_{FP} V^2$$

Since we are using the rotary-wing UAV, we adopt the rotary-wing UAV flight power consumption model from [10], which is given as:

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$$P(V) = P_0\left(1+\frac{3V^2}{U_{\text{tip}}^2}\right) + P_i\left(\sqrt{1+\frac{V^4}{4v_0^4}} - \frac{V^2}{2v_0^2}\right)^{1/2} + \frac{1}{2}d_0\rho s A_p V^3,$$

where P_0 Blade profile power, P_i Induced power, U_{tip} Rotor blade tip speed, v_0 Rotor induced velocity, d_0 Fuselage drage ratio, ρ Air density, s Motor solidity, A_p Rotor disc area.

Hence, the total energy consumption of the UAV can be expressed as:

$$E_{\text{tot}} = \tau P_c + \int_0^T P\left(V(t)\right)dt,$$

where τ is the communication time and T is the total flight time of the UAV.

We use the following values used in [10], for a UAV flight in an ideal environment to plot the relation between energy consumption and flight time as follows.

Table 1: Statistics for power consumption

Notation	Physical meaning	Value
W	UAV weight in Newton	20
ρ	Air density in kg/m^3	1.225
S_{FP}	Fuselage equivalent flat plate area in m^2	0.0151
R	Rotor radius in meter (m)	0.4
A	Rotor disc area in m^2	0.503
Ω	Blade angular velocity in radians/second	300
d_0	Fuselage drag ratio	0.6
s	Rotor solidity	0.05
δ	Profile drag coefficient	0.012
k	Incremental correction factor to induced power	0.1
m	UAV mass in kg	2.04
g	Gravitational acceleration in m/s^2	9.8

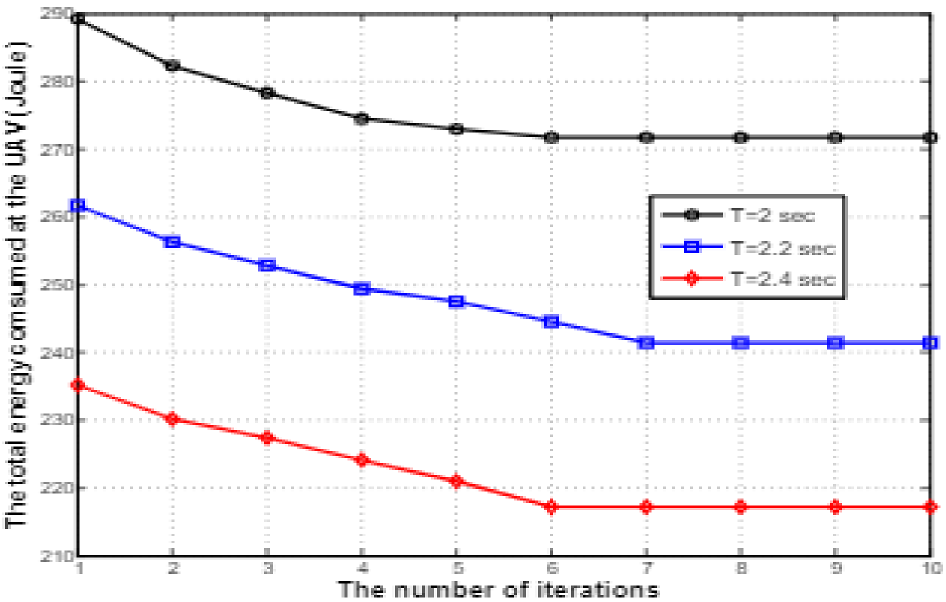

Fig 5: The total energy consumed at the UAV versus the number of iterations T

2.4 Harvested energy calculation

The energy harvested at a typical UE in unit time is expressed as $E_k = \xi P_{r,k}$ where $\xi \in (0, 1]$ is the rectifier efficiency, and $P_{r,k}$ is the total received power given as:

$$P_{r,k} = S_k + \sum_{j=0}^{1} I_{j,k} \quad \text{for} \quad k = 0, 1,$$

The overall efficiency ($\eta_{overall}$) of a UAV energy harvesting system can be defined as:

$$\eta_{overall} = \frac{\text{Unit Harvested Energy}}{\text{Total Power Consumption}}$$

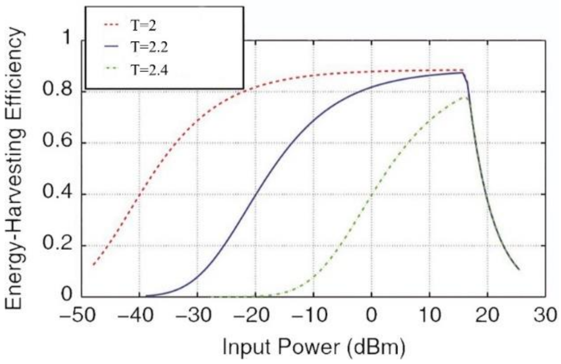

Fig 6: Energy Harvesting Efficiency

III. CONCLUSION

From the plotted graphs, we can conclude that the total harvested energy is indirectly proportional to the height of the UAV and the total flying time. However, the average energy harvested from a UE lies in the range of 10^{-3} J, which is only suitable for low-energy applications such as wireless sensors. The harvesting efficiency also varies greatly depending on the flight time and total power consumption. The maximum efficiency achieved was 83.2%, which would be even lower in a real-world environment.

Since the average harvested power is low and the efficiency is varying greatly on certain parameters, it is not suitable for a high energy system such as an UAV BS. It can still be used as a source of backup power supply during emergencies

IV. FUTURE WORK

Today, energy harvesters do not usually produce enough energy to perform mechanical work, however they provide small amounts of power to support low-energy electronics. The average energy harvested from a UE lies in the range of 10^{-3} J, so we need to develop an algorithm to simulate harvesting from multiple UEs both in LOS and NLOS.

The current formulae neglect the change in altitude during energy harvesting and the formulae is only valid for a fixed value of H.

Widely spread UEs result in a decrease in the total energy coverage probability of the network for both LOS probability models. For a certain cluster size, there exists an optimal UAV height that maximizes the network energy coverage. However, this optimal height depends on the type of the LOS probability model.

Energy harvesting is becoming more feasible today because of the increased efficiency of devices capable of capturing, storing, and producing electrical energy. This can be accomplished with the help of very efficient, very low-voltage input step-up converters. Also, improved low-voltage, high-efficiency microprocessors may allow them to become participants in energy harvesting systems.

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