SOLAR AND LASER BEAM ENERGY HARVESTING FOR UAV UNDER CLOUD EFFECT

Le Tung Hoa, Dang The Ngoc
Wireless Systems and Applications Laboratory
Posts and Telecommunications Institute of Technology

Abstract**—** In future networks, UAVs (unmanned aerial vehicles) will be essential devices for fulfilling our dream of a 3D network with many flying network devices in the sky and space. However, the lack of suitable and durable energy sources causes low performance and intermittent service in UAV-based networks. This paper evaluates an energy harvesting strategy for UAVs from sunlight and laser beams on cloudy days with a low-level cloud layer. The channel models and harvested powers for both cases are considered and analyzed using mathematical equations and simulation results.

Keywords**—**UAV, energy harvesting, solar energy, laser beam energy, cloud effect, FSO.

I. INTRODUCTION

Nowadays, human has been moving into an era of mega-connection. We have witnessed the booming of many new types of applications based on the Internet, such as digital commercials, online business, social media, online study, and so on. But even more fantasy applications have been on the way to launch shortly, which requires a well-prepared network to support them. The terrestrial network may not rely only on the infrastructure installed on the Earth's surface but also on some flying devices like UAVs. In [1] and [2], the authors already mentioned the role of UAVs in 5G and considered them a new approach from the sky. As categorized in [3], a UAV can be an aerial base station or a relay in 5G. In [4], the three main advantages of UAVs that make them a promising solution to substitute or complement terrestrial cellular networks are the LOS links, quick and flexible deployment, and a multi-UAV network. Those unique characteristics make them ideal for a variety of networking applications [4-8], including:

- Providing connectivity in disaster areas or remote locations: UAVs can be quickly deployed to provide connectivity to areas that have been affected by natural disasters or that are otherwise difficult to reach with traditional terrestrial infrastructure.
- Extending the coverage and capacity of cellular networks: UAVs can be used to extend the coverage and capacity of cellular networks, especially in areas with high traffic demand or where it is difficult to deploy traditional base stations.

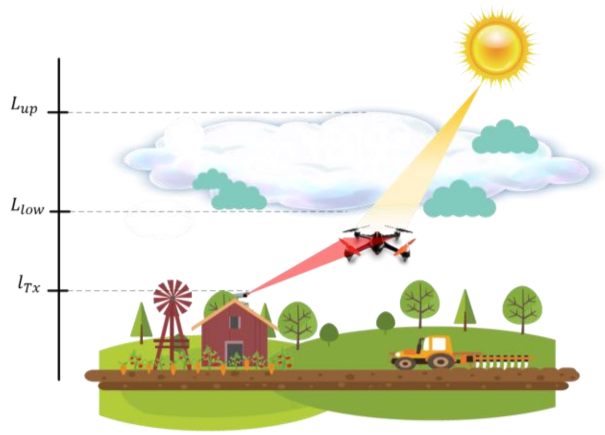


Fig 1. The harvested energy and communication system of UAV from sunlight and a laser beam

- Providing backhaul connectivity for small cells: UAVs can be used to provide backhaul connectivity for small cells, which are being deployed in large numbers to support 5G and beyond networks.
- Improving the performance of edge computing: UAVs can be used to bring computing resources closer to the edge of the network, which can improve the performance of latency-sensitive applications such as augmented reality and virtual reality.

Moving toward 6G, we have heard about a new concept of the 3D network that includes some network devices in the sky. Therefore, UAV is certainly one of the crucial elements in the 3D network, as mentioned in [9] and [10]. Thus, we have no doubt about the importance of UAVs in our future network, and many researchers have worked so hard to bring those ideas to reality.

All the above roles of UAVs in the future network are restricted by their limited energy capacity. UAVs are powered by batteries or other energy supplies, which have a finite amount of energy. This means that UAVs can only fly for a certain amount of time before they need to be recharged. This limitation can be particularly problematic for applications that require UAVs to fly long distances or to operate in remote areas. In order to tackle this

Contact author: Le Tung Hoa
Email: hoalt@ptit.edu.vn
Manuscript received: 10/2023, revised: 11/2023, accepted: 12/2023.

challenging problem, there are two main approaches: reduce energy consumption and harvest the energy, as mentioned in [11]. The first solution is to use energy the most efficiently by making optimal trajectory planning, resource allocation, and communication protocol design. However, it can extend the lifespan of a UAV but it cannot solve completely the problem. The second approach, an in-flight UAV collects energy to be self-powered by the surrounding environment or wireless charging. The two outstanding candidates representing to the second idea are solar charging and FSO wireless charging, respectively.

The first problem-solving method, the environmental energy harvesting from sunlight has been studied and applied to UAVs by many researchers. This type of UAV is the so-called solar-powered UAV (SUAV). In [12], authors used a set of drones equipped with solar panels to build a network chain without the need for an electricity grid and communication infrastructure. The research in [13] investigated the joint optimization of 3D position, power, and subcarrier allocation of SUAVs to maximize total system throughput. Another in [14] proposed online and suboptimal algorithms for resource management of SUAVs, considering solar energy harvesting, aerodynamic power consumption, onboard energy storage dynamics, and QoS requirements for terrestrial users. [15] focused on the feasibility of EH technology for SUAVs and proposed two schemes to optimize its performance, while [14] and [16] focused on establishing a solar UAV communication system and considering the impact of clouds on solar energy collection. So, SUAV is a part of the current research stream which has caught lots of attention.

The second problem-solving method, laser-powered UAV wireless communication systems, well-known as free space optics (FSO) systems for UAVs, has the potential to provide convenient and sustainable energy to UAVs. Researchers have studied different aspects of these systems. [17] focused on optimizing the performance of laser-powered UAV wireless communication systems. In a further step, the idea of simultaneously transferring data and charging UAVs using optical signals was further developed in [18-19]. This is known as simultaneous lightwave information and power transfer (SLIPT), SLIPT is particularly attractive for UAV applications because it can provide high-speed data transfer and efficient energy harvesting over long distances.

In all the mentioned research, authors have seemingly considered those two promising charging methods separately. Our paper contributes to putting them in one scenario including cloud appearance to clarify their usage. We evaluate our harvested energy with the presence of the cloud effect to make a clearer comparison between solar and laser-beam supplementations. All evaluations first are introduced by mathematical equation explanation. Then, some simulations are carried out to have a quantitative comparison.

II. CLOUD EFFECT

Natural clouds are visible masses of condensed water vapor floating in the Earth's atmosphere. They are formed when water vapor rises and cools, causing it to turn into tiny water droplets or ice crystals. Clouds play an important role in the Earth's climate by reflecting sunlight into space and by trapping heat. However, clouds are one of the main factors causing a significant attenuation in our charging systems from solar radiation and laser radiation resources. In the former, the sun radiates sunlight whose spectrum spreads from visible light to infrared light [20]. In the latter, FSO communications, also known as optical wireless (OW) or infrared laser, is a technology that uses modulated visible or infrared (IR) light beams to transmit data through the atmosphere. Like fiber optic communication, FSO uses lasers to transmit data, but instead of transmitting the data stream through a glass fiber, it is transmitted through the air where clouds may exist. Therefore, clouds can degrade the energy harvesting efficiency because most solar power and laser beam is in the frequency range of visible and infrared light, which has wavelengths smaller than 1 mm. This means that cloud droplets, which have radii ranging from $5\ \mu m$ to $5\ mm$, can reflect or scatter a large portion of those power resources, reducing the amount of energy that the UAV can collect [20][21].

In order to determine the concentration of clouds that absorb light, the Beer-Lambert law is applied. The cloud attenuation of solar light and laser beam rays can be calculated as [21][22]

$$h_c = \exp\left(-\alpha_c L_c\right), \tag{1}$$

where $\alpha_c \geq 0$ and L_c represent the Mie scattering coefficient of the cloud and the distance that they pass through the cloud. In other words, L_c shows the path inside of the cloud in which solar light and laser beam signals are undergone.

III. SYSTEM AND CHANNEL MODELS

3.1. System model

Our system model, as depicted in Fig.1, contains a flying UAV that receives some optical signals from a transmitter with a laser implemented on a building via FSO communication. However, we not only consider the data stream via the FSO link but also the charging techniques for extending the lifespan of the in-flight UAV. There are two different ways to charge the UAV, which are solar and laser-beam supplementations. In the former, the UAV is powered by sunlight from the Sun. In the latter, the FSO link which we use to convey our data stream can also carry energy to supplement the UAV through SLIPT mechanism. We assume our UAV to fly at a height below $1800m$ and thus to be exposed to a low-lever cloud Stratus. The cloud is formed from the lower edge, $L_{low} = 700m$ to the upper edge, $L_{up} = 1400m$.

3.2. Sunlight channel model for solar energy harvesting with cloud effect

While propagating from the Sun to the solar panels, sunlight, located at a spectrum range from visible to infrared frequency, suffers some natural factors, such as atmospheric transmittance (h_{at}) and cloud attenuation (h_{c_solar}). Therefore, the total channel for solar energy harvesting can be estimated as

$$h_{solar} = h_{at} h_{c\_solar}, \quad (2)$$

a. Atmospheric transmittance h_{at}

In [23], sunlight rays are radiated from the Sun and transferred through the atmospheric environment which absorbs a part of the energy and causes energy reduction. The atmospheric transmittance is modelized by the following equation:

$$h_{\text{at}} = 0.8978 - 0.2804\exp\left(-\frac{l}{3500}\right), \quad (3)$$

where l is the altitude of the UAV carrying the solar panel to collect solar energy. The equation is achieved from the LOWTRAN 7 [23] software. Based on it, at the higher altitude which is closer to the Sun, the value of the atmospheric transmittance is bigger. Consequently, that affects positively the increasing amount of the harvested energy.

b. Cloud attenuation h_{c_solar}

The atmospheric environment includes not only air molecules but also lots of cloud layers. As discussed in section II, the sunlight rays also witness the cloud attenuation as modelized in Eq. (1).

In above equation, h_{c_solar} represents the cloud attenuation of solar light rays depending on the correlation between the UAV height and the cloud height. The value of h_{c_solar} can be described as

$$h_{c\_solar}(l) = \begin{cases} 1, & if\ l \geq L_{up} \\ e^{-\alpha_{c\_solar}(L_{up}-l)}, & if\ L_{low} \leq l < L_{up} \\ e^{-\alpha_{c\_solar}(L_{up}-L_{low})}, & if\ l < L_{low} \end{cases}, \quad (4)$$

where α_{c_solar} is the absorption coefficient of cloud when sunlight passes through. Based on equation (4), when the UAV flies above the cloud, the cloud does not affect to the harvested solar power. However, the UAV reduces its altitude and flies into the cloud, the solar power decreases due to the distance from the upper edge of the cloud to the current UAV position. When the UAV gets through the cloud to be closer to the Earth's surface, h_{c_solar} now becomes a constant value that is determined by the thickness of the cloud, $L_{up} - L_{low}$.

3.3 FSO channel model for laser beam energy harvesting and communication with cloud effect

The laser beam is created at a laser of the transmitter and carries optical signals. Those signals are transmitted via an FSO channel. The FSO channel takes into account three main factors: atmospheric attenuation (h_l), beam spreading loss (h_{p}), turbulence (h_t) and cloud attenuation (h_{c_FSO}). The total channel h_{FSO} is shown in the following equation

$$h_{FSO} = h_l h_{\text{p}} h_t h_{c\_FSO}. \quad (5)$$

a. Atmospheric attenuation h_l

The phenomenon of energy decrease that occurs when optical signals are carried across a specific distance in the air is expressed by atmospheric attenuation. The reduction occurs as a result of the laser beam energy being absorbed by gas molecules and aerosol particles that are naturally in the air. Thus, the greater the distance, the greater the loss. Following the Beer-Lambert law in [24], the path loss h_l of the FSO channel is calculated as follows

$$h_l = \exp(-\sigma_{air} L), \quad (6)$$

where L is the propagation distance length, and σ_{air} is the atmosphere attenuation parameter.

$$\sigma_{air} = 10log_{10}(E_u)\frac{3.912}{V_{air}[km]}\left(\frac{\lambda[nm]}{550}\right)^{-q_{air}(V_{air})}, \quad (7)$$

where E_u is the Euler's constant, λ is the wavelength in the FSO system, V_{air} is the visibility, and q_{air} is the specific atmospheric attenuation visibility coefficient.

b. Beam spreading loss h_p

When a lazer beam propagates through a wireless channel, its footprint is expanded. Thus, the beam spreading loss. h_{p} aims to give a portion between the receiver's aperture and the size of beam footprint and can be estimated as

$$h_{\text{p}} \approx A_0 exp\left(-\frac{2r^2}{w_{zeq}^2}\right), \quad (8)$$

where r is the radial displacement at the receiver, w_{zeq} is the equivalent beam radius, and A_0 is the fraction of the collected power at $r = 0m$.

b. Atmospheric turbulence h_t

The random fluctuations in temperature, pressure, and wind that occur both in space and time are known as atmospheric turbulence [25]. h_t, can be represented as the product of turbulent eddies on the small- and large-scales, α and β, respectively, and its probability density function (PDF) can be written as

$$f_{h_t}(h_t) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_t^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_t}\right), \quad (9)$$

where $\Gamma(.)$ represents the gamma function and $K_v(.)$ is the v-th order modified Bessel function of the second kind. Both α and β can be estimated as follows

$$\alpha = \left[exp\left(\frac{0.49\sigma_R^2}{(1+1.11\sigma_R^{12/5})^{7/6}}\right) - 1\right]^{-1}, \quad (10)$$

$$\beta = \left[exp\left(\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{12/5})^{5/6}}\right) - 1\right]^{-1}, \quad (11)$$

where σ_R^2 is the Rytov variance. For the plane wave, σ_R^2 can be given as

$$\sigma_R^2 = 2.25k^{7/6}[\sec(\zeta)]^{11/6} \int_{l_{Tx}}^{l} C_n^2(h)(h - l_{Tx})^{5/6} dh, \quad (12)$$

where $k = 2\pi/\lambda$ is the optical wave number, $C_n^2(h)$ is the refractive-index structure parameter, and l is the height of UAV, l_{Tx} is the height of transmitter on the Earth and ζ is the zenith angle of the transmitter. The Hufnagel Valley Boundary (HVB) [26] is applied to model $C_n^2(h)$ as follows

$$C_n^2(h) = 0.00594\frac{w^2}{729}(10^{-5}h)^{10} exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} exp\left(-\frac{h}{1500}\right) + C_n^2(0) exp\left(-\frac{h}{100}\right), \quad (13)$$

where $w[\frac{m}{s}]$ is the wind velocity and h is the height above the Earth's surface. $C_n^2(0)$, the turbulence at ground, can be given as

$$C_n^2(0) = 1.29 \times 10^{-12} r_0^{-\frac{5}{3}} \lambda^2 - 1.61 \times 10^{-13} \theta_0^{-\frac{5}{3}} \lambda^2 + 3.89 \times 10^{-15}, \quad (14)$$

where r_0 is the atmospheric coherence length and θ_0 is the isoplanatic angle. In general, w and $C_n^2(0)$ are assigned to 21 (m/s) and 5×10^{-13} (m/s), respectively.

c. Cloud attenuation h_{c_FSO}

The parameter α_c in equation (1) expresses how much clouds affect the signals passing through. In our FSO link, the α_c can be replaced by a specific variable $\alpha_{\mathrm{c\_FSO}}$. Thus, h_{c-FSO} can be estimated by the following equation

$$h_{c\_FSO} = \exp\left(-\alpha_{c\_FSO} L_{c\_FSO}\right), \quad (15)$$

where L_{c_FSO} is the distance of optical signal passing through the cloud. It can be calculated as

$$L_{c\_FSO} = \begin{cases} L_{up} - L_{low}, & if\ l \geq L_{up} \\ l - L_{low}, & if\ L_{low} \leq l < L_{up} \\ 0, & if\ l < L_{low} \end{cases}, \quad (16)$$

The value of $\alpha_{\mathrm{c\_FSO}}$ is based on each cloud type. We can classified clouds by the attitude, but to model the effect of clouds into our systems in FSO link, we focus on two main parameters of clouds which are cloud droplet number concentration, $N_c(cm^{-3})$, and cloud liquid water content $M_c(g/m^3)$. Those two parameters contribute to measure the visibility V (km) as following [27]:

$$V = \frac{1.002}{(N_c x M_c)^{0.6473}}. \quad (17)$$

For example [27], the low-level cloud Stratus existing below 1.8 km compared to the Earth's surface has $250\ (cm^{-3})$ to N_c and $0.29\ (g/m^3)$ to M_c. While the middle-level cloud Altostratus is from 1.8 – 6 km above to the Earth's surface, N_c and M_c are $400\ (cm^{-3})$ and $0.41\ (g/m^3)$, respectively.

Once we have the visibility V (km) we can estimate $\alpha_{\mathrm{c\_FSO}}$ through the dependent empirical model

$$\alpha_{\mathrm{c\_FSO}} = \frac{3.91}{V[km]} \left(\frac{\lambda[nm]}{550}\right)^{-q(V)} \quad (18)$$

where λ denotes the signal wavelength and q denotes the coefficient relying to the size distribution of scattering particles. In [28], q is estimated from empirical models and specified by Kim model as follows:

$$q = \begin{cases} 1.6, & if\ V > 50 \\ 1.3, & if\ 6 < V \leq 50 \\ 0.16V + 0.34, & if\ 1 < V \leq 6 \\ V - 0.5, & if\ 0.5 < V \leq 1 \\ 0, & if\ V \leq 0.5 \end{cases}, \quad (19)$$

IV. COMMUNICATION AND ENERGY HARVESTING ANALYSIS

4.1. Solar energy harvesting

According to [22-23], the harvested solar power at the UAV implemented the solar panel is estimated by the following equation:

$$P_{solar}(l) = \eta_{SP} S_{SP}\ G h_{solar}, \quad (20)$$

where η_{SP} and S_{SP} are parameters for the solar panels installed on the UAV's wings. They are the solar cell efficiency and the total size of solar panel, respectively. G is the average solar radiation from the Sun. However, to obtain $P_{solar}(l)$, the UAV has to carry the solar panel, which consumes more energy. The trade-off is lifted in the paper's scenario to reduce the complexity.

4.2. SPLIT mechanism for communication and laser beam energy harvesting

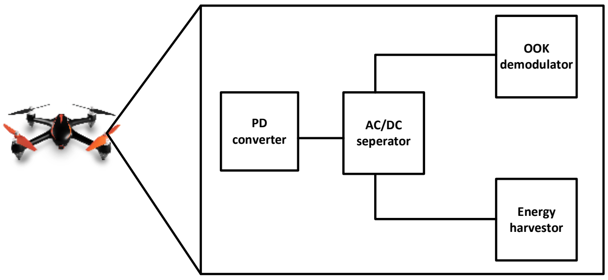


Fig 2. SPLIT mechanism to simultaneously transfer data and energy

In our FSO link, the simplest modulation on-off keying (OOK) is used. At the transmitter, the electrical signals carrying bit streams are represented as

$$b(t) = \begin{cases} A\ for\ transmitting\ bit\ '1' \\ -A\ for\ transmitting\ bit\ '0' \end{cases}, \quad (21)$$

where A is the peak amplitude. Then the signals, $b(t)$, are added a DC bias B to make sure of a non-negative value afterward. The correlation between A and B is given by

$$A = \begin{cases} B - I_L\ if\ B < (I_L + I_H)/2 \\ I_H - B\ if\ B \geq (I_L + I_H)/2 \end{cases}, \quad (22)$$

where I_L and I_H are the lowest and highest input bias currents, respectively. To convert the electrical to optical signals, a laser diode (LD) with a power P_{LD} is used. Consequently, if ξ is the electrical-to-optical conversion coefficient, the optical signal from the transmitter can be described as the following

$$P_t(t) = P_{LD}[B + \xi b(t)]. \quad (23)$$

The signal propagates through an FSO channel, modelized by h_{FSO}, to reach to a receiver of the UAV. In Fig.2, the optical signal is first switched back into the electrical domain by using a PD converter. The electrical signal can be expressed as

$$i(t) = \mathcal{R} S_a h_{FSO} P_t(t) + n(t), \quad (24)$$

where $\mathcal{R}$ and S_a are parameters for the PD. They are the PD responsivity and PD size, respectively. *n(t)* is the additive white Gaussian noise (AWGN) term with zero mean and variance of σ_n^2. The receiver applies SPLIT mechanism to split the received electrical signal into the DC part (I_{DC}) for the charging target and the AC part ($I_{AC}(t)$) for the communication target. So, the electrical signal also can be formulated as

$$i(t) = I_{DC} + I_{AC}(t) + n(t). \quad (25)$$

Based on the above equations, we can get the following values

$$I_{DC} = \mathcal{R} S_a h_{FSO} P_{LD} B, \quad (26)$$

$$I_{AC}(t) = \mathcal{R} S_a h_{FSO} P_{LD} \xi b(t). \quad (27)$$

According to [29], the harvested energy E_{FSO} can be estimated as

$$E_{FSO} = \frac{0.75 T_{EH} V_t {I_{DC}}^2}{I_d} = \frac{0.75 T_{EH} V_t (\mathcal{R} S_a h_{FSO} P_{LD} B)^2}{I_d} \quad (28)$$

where T_{EH} is the harvesting time, V_t is the thermal voltage and I_d is the dark saturation current of the solar panel. Therefore, the power collected by the FSO link can be expressed as

$$P_{FSO} = \frac{E_{FSO}}{T_{EH}} = \frac{0.75V_t(\mathcal{R}S_a h_{FSO} P_{LD} B)^2}{I_d}. \quad (29)$$

Because the FSO channel h_{FSO} is described by a PDF function, the average value of power collected by the FSO link is estimated by

$$\overline{P_{FSO}} = \int_0^\infty \frac{0.75V_t(\mathcal{R}S_a f(h_{FSO}) P_{LD} B)^2}{I_d} dh_{FSO}. \quad (30)$$

In order to evaluate the quality of our communication, the bit error probability P_b when using OOK modulation scheme is estimated as

$$P_b = Q(\sqrt{SNR}) = Q\left(\sqrt{\frac{(\mathcal{R}S_a h_{FSO} P_{LD} \xi A)^2 T_s}{N_0}}\right), \quad (31)$$

where T_s is symbol duration and N_0 is the power spectral density of AWGN. Since the FSO channel h_{FSO} equation is described by PDF, the average value of $\overline{P_b}$ is calculated as

$$\overline{P_b} = \int_0^\infty Q\left(\sqrt{\frac{(\mathcal{R}S_a f(h_{FSO}) P_{LD} \xi A)^2 T_s}{N_0}}\right) dh_{FSO}. \quad (32)$$

V. NUMERICAL RESULTS

This section is to provide some results to help us analyze the impact of the cloud on the harvesting process and our communication quality. All parameters are described in detail in Table 1.

Table 1. Simulation parameters

System parameter		
Height of transmitter	l_{Tx}	$10m$
Lower edge of cloud	L_{low}	$700m$
Upper edge of cloud	L_{up}	$1400m$
Parameter for sunlight link		
Absorption coefficient of cloud for sunlight	α_{c_solar}	0.01
Solar cell efficiency	η_{SP}	0.4
Size of solar panel	S_{SP}	$0.1m^2$
Average solar radiation	G	$1367W/m^2$
Parameter for FSO link		
Wavelength	λ	$1550\ nm$
Visibility	V_{air}	$30\ km$
Atmospheric attenuation visibility coefficient	q_{air}	1.3
Droplet number concentration of Stratus cloud	N_c	$250\ cm^{-3}$
Liquid water content of Stratus cloud	M_c	$0.29\ g/m^3$
Minimum input bias current	I_L	$25\ mA$
Maximum input bias current	I_H	$45\ mA$
LD power	P_{LD}	$30\ W/A$
Electrical-to-optical conversion coefficient	ξ	0.9
DC bias	B	$35\ mA$
Responsibility	$\mathfrak{R}$	$0.8\ A/W$
PD size	S_a	$0.1m^2$
Thermal voltage	V_t	$25\ mV$
Dark saturation current of PD	I_d	$10^{-9}\ A$
Power spectral density of noise	N_0	10^{-14} W/Hz
Symbol duration	T_s	$1\ \mu s$

The first result, in Fig.3, shows how much cloud affects the energy harvesting from the Sun. When the UAV flies higher which means closer to the radiation resource, the Sun, the more energy the UAV collects. In a clear sky condition, the collected power increases slightly from $36W$ to $39W$ when the UAV moves from the height of $500m$ to $1500m$. However, the harvested energy drops significantly from $38W$ to $0.03W$ at the two edges of the clouds $L_{up} = 1400m$ to $L_{low} = 700m$, respectively.

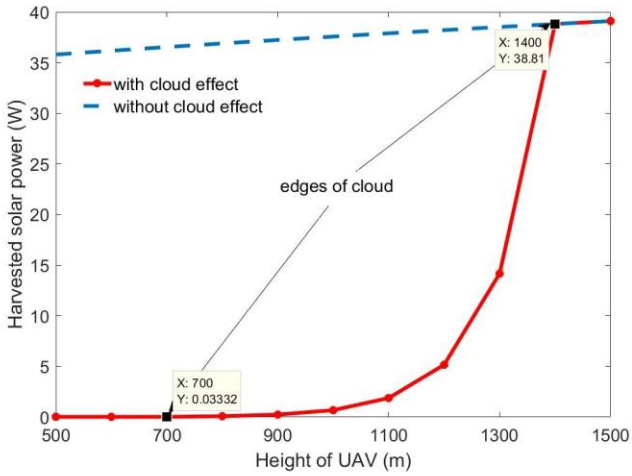


Fig 3. The harvested solar power over the height of the UAV with and without cloud effect.

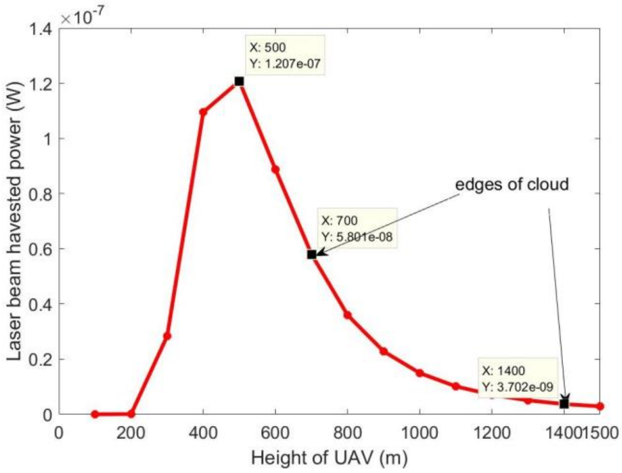


Fig 4. The laser beam harvested power over the height of the UAV under cloud effect

The second result, in Fig.4, depicts the amount of energy harvesting via FSO link to a flying UAV with the cloud effect consideration. Because the FSO link is strongly influenced by complicated turbulence, even the lower altitude of the UAV does not go along with the more collected energy. The highest power is harvested when the UAV flies below the cloud and stays at 500m height.

Moreover, the affection of clouds in this harvesting process is the same as solar energy. The harvested power drops nearly ten times (from $5.8\,x10^{-8}$ to $3.7\,x10^{-9}$) when the laser beam passes through the cloud (from $700m$ to $1400m$) to reach the UAV.

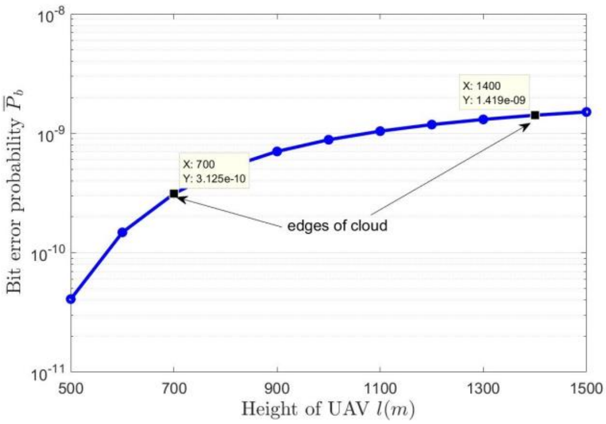


Fig 5. The bit error probability $\overline{P_b}$ over the height of UAV under cloud effect

Lastly, Fig 5 is made to evaluate the communication quality of the FSO link. The higher the UAV stays, the higher the bit error probability is. However, at any height, lower than $1500m$, the value of P_b remains smaller than 10^{-9} which can be considered as an error-free link.

VI. CONCLUSION

In the future network ecosystem, UAVs will play a role in linking many devices of the existing terrestrial networks to many more flying devices in the sky and even in space. The UAV performance is strongly affected by energy limitation. A potential strategy for dealing with it is energy harvesting. The paper has considered the solar and laser beam charging methods under a challenging condition, which includes a low-level cloud layer. The solar energy reduces significantly when the sunlight passes through the cloud layer. The harvested energy from a laser beam witnesses the same tendency with a reduction when transmitting through a cloud. However, the FSO link with turbulence phenomena causes a more complicated and unpredictable result. The most collected energy happens when the UAV's height is below the cloud but not near the transmitter. The research in this paper is the beginning to develop the idea and bring UAVs to our network.

REFERENCES

[1] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on uav communications for 5g and beyond," Proceedings of the IEEE, vol. 107, no. 12, pp. 2327–2375, 2019.

[2] M. Erdelj, E. Natalizio, K. R. Chowdhury, and I. F. Akyildiz, "Help from the sky: Leveraging uavs for disaster management," IEEE Pervasive Computing, vol. 16, no. 1, pp. 24–32, 2017.

[3] Z. Ullah, F. Al-Turjman, and L. Mostarda, "Cognition in uav-aided 5g and beyond communications: A survey," IEEE Transactions on Cognitive Communications and Networking, vol. 6, no. 3, pp. 872–891, 2020.

[4] B. Li, Z. Fei, and Y. Zhang, "Uav communications for 5g and beyond: Recent advances and future trends," IEEE Internet of Things Journal, vol. 6, no. 2, pp. 2241–2263, 2019.

[5] O. M. Bushnaq, A. Chaaban and T. Y. Al-Naffouri, "The Role of UAV-IoT Networks in Future Wildfire Detection," in IEEE Internet of Things Journal, vol. 8, no. 23, pp. 16984-16999, 1 Dec.1, 2021.

[6] Xia, Xiaoyu & Fattah, Sheik & Ali Babar, Muhammad, "A Survey on UAV-enabled Edge Computing: Resource Management Perspective", 2022.

[7] F. Zhou, R. Q. Hu, Z. Li and Y. Wang, "Mobile Edge Computing in Unmanned Aerial Vehicle Networks," in *IEEE Wireless Communications*, vol. 27, no. 1, pp. 140-146, February 2020.

[8] Abubakar, A. I., Ahmad, I., Omeke, K. G., Ozturk, M., Ozturk, C., Makine, A., Mollel, M. S., Abbasi, Q. H., Hussain, S., & Imran, M. A. , "A Survey on Energy Optimization Techniques in UAV-Based Cellular Networks: From Conventional to Machine Learning Approaches. Drones," 7(3), 214, 2023.

[9] E. Calvanese Strinati, S. Barbarossa, T. Choi, A. Pietrabissa, A. Giuseppi, E. De Santis, J. Vidal, Z. Becvar, T. Haustein, N. Cassiau, F. Costanzo, J. Kim, and I. Kim, "6g in the sky: On-demand intelligence at the edge of 3d networks (invited paper)," ETRI Journal, vol. 42, no. 5, pp. 643–657, 2020.

[10] I. F. Akyildiz, A. Kak, and S. Nie, "6g and beyond: The future of wireless communications systems," IEEE Access, vol. 8, pp. 133995–134030, 2020.

[11] Huilong Jin, Xiaozi Jin, Yucong Zhou, Pingkang Guo, Jie Ren, Jian Yao, Shuang Zhang, "A survey of energy efficient methods for UAV communication," Vehicular Communications, vol. 41, 2023.

[12] Woźniak, Wiktor & Jessa, Mieczysław, "Selection of Solar Powered Unmanned Aerial Vehicles for a Long Range Data Acquisition Chain" Sensors (Basel, Switzerland). 21. 10.3390/s21082772, 2021.

[13] Y. Sun, D. Wing Kwan Ng, D. Xu, L. Dai and R. Schober, "Resource Allocation for Solar Powered UAV Communication Systems," *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Kalamata, Greece, 2018, pp. 1-5, doi: 10.1109/SPAWC.2018.8445944.

[14] Y. Sun, D. Xu, D. W. K. Ng, L. Dai and R. Schober, "Optimal 3D-Trajectory Design and Resource Allocation for Solar-Powered UAV Communication Systems," in *IEEE Transactions on Communications*, vol. 67, no. 6, pp. 4281-4298, June 2019.

[15] A. Ali and M. O. Hasna, "Energy Harvesting Schemes for UAV based Communications," *2019 16th IEEE Annual Consumer Communications & Networking Conference (CCNC)*, Las Vegas, NV, USA, 2019, pp. 1-2, doi: 10.1109/CCNC.2019.8651812.

[16] X. He, J.A. Hong, A. Frs, L.A. Ying, A. Lpd, "Energy efficient resource allocation in delay-aware UAV-based cognitive radio networks with energy harvesting", Sustain. Energy Technol. Assess. 45 (2021).

[17] J. Ouyang, Y. Che, J. Xu, K. Wu, "Throughput maximization for laser-powered UAV wireless communication systems," 2018 IEEE International Conference on Communications Workshops, ICC Workshops, IEEE, 2018, pp.1–6.

[18] P. D. Diamantoulakis, G. K. Karagiannidis, and Z. Ding, "Simultaneous lightwave information and power transfer (slipt)," IEEE Transactions on Green Communications and Networking, vol. 2, no. 3, pp. 764–773, 2018.

[19] Y. L. Che, W. Long, S. Luo, K. Wu, and R. Zhang, "Energy-efficient uav multicasting with simultaneous fso backhaul and power transfer," IEEE Wireless Communications Letters, vol. 10, no. 7, pp. 1537-1541, 2021.

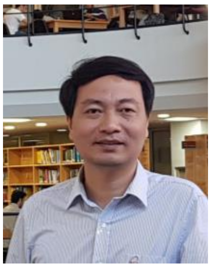
[20] Zhang, Jing, et al. "Power cognition: Enabling intelligent energy harvesting and resource allocation for solar-powered UAVs." Future Generation Computer Systems 110 (2020): 658-664.
[21] Nguyen, Thang V., Hoang D. Le, Ngoc T. Dang, and Anh T. Pham. "On the design of rate adaptation for relay-assisted satellite hybrid FSO/RF systems." IEEE Photonics Journal 14, no. 1 (2021): 1-11.
[22] Sun, Yan, Dongfang Xu, Derrick Wing Kwan Ng, Linglong Dai, and Robert Schober. "Optimal 3D-trajectory design and resource allocation for solar-powered UAV communication systems." IEEE Transactions on Communications 67, no. 6 (2019): 4281-4298.
[23] Lee, Joo-Seok, and Kee-Ho Yu. "Optimal path planning of solar-powered UAV using gravitational potential energy." IEEE Transactions on Aerospace and Electronic Systems 53, no. 3 (2017): 1442-1451.
[24] T. V. Nguyen, T. V. Pham, N. T. Dang, and A. T. Pham, “Performance of generalized qam/fso systems with pointing misalignment and phase error over atmospheric turbulence channels,” IEEE Access, vol. 8, pp. 203631– 203644, 2020.
[25] A. C. Motlagh, V. Ahmadi, Z. Ghassemlooy, and K. Abedi, “The effect of atmospheric turbulence on the performance of the free space optical communications,” in 2008 6th International Symposium on Communication Systems, Networks, and Digital Signal Processing, pp. 540–543, 2008
[26]H. Kaushal and G. Kaddoum, “Optical communication in space: Challenges and mitigation techniques,” IEEE Commun. Surveys Tuts., vol. 19, pp. 57–96, First quarter 2017.
[27]Awan, Muhammad Saleem, E. Leitgeb, B. Hillbrand, F. Nadeem, and M. S. Khan. "Cloud attenuations for free-space optical links." In 2009 International Workshop on Satellite and Space Communications, pp. 274-278. IEEE, 2009.
[28] Le, Hoang D., Thang V. Nguyen, and Anh T. Pham. "Cloud attenuation statistical model for satellite-based FSO communications." IEEE Antennas and Wireless Propagation Letters 20, no. 5 (2021): 643-647.
[29] Rakia, Tamer, Hong-Chuan Yang, Fayez Gebali, and Mohamed-Slim Alouini. "Optimal design of dual-hop VLC/RF communication system with energy harvesting." IEEE Communications Letters 20, no. 10 (2016): 1979-1982.

THU THẬP NĂNG LƯỢNG TỪ MẶT TRỜI VÀ CHÙM LASER CHO UAV DƯỚI ẢNH HƯỞNG CỦA MÂY

Tóm tắt- Trong các mạng tương lai, UAVs (thiết bị bay không người lái) sẽ trở thành các thiết bị thiết yếu để thỏa mãn ước vọng của một mạng 3 chiều với nhiều thiết bị mạng bay trong không trung và vũ trụ. Tuy nhiên, việc thiếu các nguồn năng lượng bền vững và lâu dài khiến mạng dựa trên UAV hoạt động kém hiệu quả và gián đoạn. Bài báo này đánh giá một chiến lược thu thập năng lượng cho UAV từ ánh sáng mặt trời và tia laser vào những ngày nhiều mây với lớp mây thấp. Các mô hình kênh và năng lượng thu được cho cả hai trường hợp được xem xét và phân tích bằng các công thức toán học và kết quả mô phỏng.

Từ khóa- Thu thập năng lượng, UAV, năng lượng mặt trời, năng lượng tia laser, ảnh hưởng của mây, truyền thông FSO.

Le Tung Hoa received B.E. from Posts and Telecommunications Institute of Technology (PTIT), Vietnam, in 2007, and M.E. degree from University of Electro-communication, Japan, in 2010, both in telecommunication engineering. Now, she is a lecturer at Faculty Telecommunication 1 of PTIT. Her research interests include wireless communications, VANET, Vehicular VLC and FSO communications.



Dang The Ngoc received the Ph.D. degree in computer science and engineering from the University of Aizu (Japan). He is currently is Associate Professor/Vice Dean of Faculty of Telecommunications and Head with the Department of Wireless Communications at Posts and Telecommunications Institute of Technology (PTIT). Dr. Ngoc was also an invited researcher/ research fellow at Universite de Rennes 1, (France), the University of Seville (Spain), and the University of Aizu. His current research interests include the area of communication theory with a particular emphasis on modeling, design, and performance evaluation of optical CDMA, RoF, QKD, and optical wireless communication systems. He is a member of IEEE.