IMPACT OF CLOUDS AND ATMOSPHERIC TURBULENCE ON HAPS-BASED FSO SYSTEMS

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Abstract**—** This work investigates a system availability of high-altitude platform station (HAPS)-based free-space optical (FSO) system based on the observed cloud data from the European Center for Medium-Range Weather Forecast (ECMWF). The collected data is, then, used to evaluated the optical link availability for several regions in Vietnam. The numerical results reveal the advantage of using site diversity to combat cloud attenuation and atmospheric turbulence.

Keywords**—**High-altitude platform station (HAPS), Cloud attenuation, Free-space optical (FSO) systems.

I. INTRODUCTION

6G wireless communication system envision to provide broadband services in underserved areas with reasonable costs. Satellite networks are one possible enabler of such a vision due to their large footprints and their capabilities to provide ubiquitous coverage to remote areas. Recently, mega-constellations of small satellites in low-earth orbit (LEO) gain interest in acamedia and industry to enable broadband services worldwide [1]. Moreover, the developlement of the integrated satellite-aerial-ground networks can further improve the coverage, reliability, and scalability of 6G wireless communication systems [2]-[4]. A potential integrated spatial network consists of spatial nodes at the same or different altitudes connected via optical links. Therein, high-altitude platform is an important node in the spatial networks since it can operate as a based station on the sky or a relaying node to forward the data from the satellite through the atmosphere to end-users (e.g., ground station, vehicle, sensors, etc.).

In this study, we consider the HAP act as a station. High-altitude platform station (HAPS) is a quasi-stationary vehicle like airships, aircraft, or balloons, placed in the stratosphere at an altitude from 17 to 25 km above Earth's surface where the impact of atmosphere on optical beam is less severe than directly above the ground. Compared with terrestrial and satellite systems, HAPS has unique characteristics such as a large coverage area (3-7 km), quick deployment, flexible capacity increase through spot beam resizing, and low maintenance cost [5, 6]. Since HAPS is placed far from the atmospheric region, thay provide a better channel condition than satellites. Moreover, it provides better light-of-sight (LOS) condition in almost all coverage areas, thereby causing less shadowing than terrestrial systems. It can act as a relay station to forward the high-capacity optical data through the atmosphere to the ground. The backhaul optical link for the HAPS is capable of connecting to the core network through terrestrial gateways stations. In case whenever HAP network is much larger than the cloud coverage correlation length, a ground station diversity can be used to improve the reliability of the system [7]. On the other hand, free-space optical communications have recently gained industry and academic attention to provide gigabit capacity backhaul links due to feasible cost and rapid deployment compared to radio frequency (RF) and optical fiber [8]. The combination of HAPS and FSO, as shown in Fig.1, is opened a new chapter for spatial communications. As shown in Fig. 1, FSO-based HAPS can work as a stand-alone system to provide high-speed connection to urban area or rural area, where is difficult to implement communications.

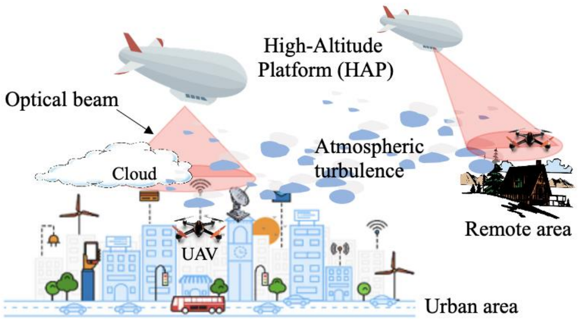

Fig. 1. HAPS-based FSO systems in urban and remote areas.

Operating over the free-space medium, the performance of the HAPS-based FSO system is significantly affected by atmospheric turbulence and cloud coverage [9], which can severely decrease the system performance, especially system availability. On the one hand, it is the power loss due to Mie scattering by particles in clouds. On the other hand, it is the random fluctuation of transmitted power caused by atmospheric turbulence. For these reasons, an investigation of link availability should be studied in planning and designing a HAPS-based FSO communication systems.

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As a matter of fact, there have been a number of studies on the estimation of link availability in the presence of cloud with/without turbulence [10, 11, 12]. Notably, Suzuki et al. collected cloud images to estimate the link availability for implementing the optical system for several regions in Japan [10]. The drawback of the method is, however, not always possible for other sites since the complexity and high-cost facilities are required. In [11, 12], the authors used another method implemented based on the cloud liquid water content (CLWC) data from available databases observed by satellites. Nevertheless, the laser links were blocked whenever CLWC > 0 as the algorithm was used in [11]. As reported in [11], the FSO link can still maintain in the presence of clouds with low CLWC. However, the satellite link availability is only investigated for Japan.

We, therefore, aim at investigating the impact of cloud attenuation and atmospheric turbulence on the HAPS-based FSO systems. First, we collect the CLWC data from the meteorological ERA-Interim database provided by European Center for Medium-Range Weather Forecast (ECMWF) [14]. Based on the methodology in [12], the data is used to estimate the link availability for several regions in Vietnam. Furthermore, the HAPS site diversity is also investigated in our work to show how the proposed technique combat the impact of cloud attenuation and atmospheric turbulence.

II. CHALLENGING ISSUES IN HAPS-BASED FSO SYSTEMS

This section will cover two main challenging issues of HAPS-based FSO communications. In particular, random phenomena like clouds and atmospheric turbulence are investigated in our work.

Fig. 1 illustrates the implementation of HAPS-based FSO systems in urban and remote areas. The optical downlink from HAPS to end-users is considered. The FSO link may be blocked or deteriorate during the transmission due to cloud coverage and atmospheric turbulence. Therefore, the observation of CLWC is essential to design the link budget. An example of the average CLWC of 5 years for Hanoi, Danang, and Hochiminh areas is depicted in Fig. 2.

A. Cloud attenuation

The presence of opaque clouds may occationally disrupt the signal or completely block the optical signal from HAP to the ground station rendering the LOS communication useless. These intermittent blockages can last from gew seconds to several hours depending on the geographical location and season. They can lead to wandering off the downlink signal from the desired position if the space-borne system relies on uplink beacon signal for tracking and pointing [13]. Clouds offer significant attenuation as high as tens of dB and therefore require necessary actions to combat the signal loss due to cloud coverage. Mathematical modeling of the FSO communication system over cloudy channel based on ECMWF database is discussed in [15].

Clouds can be characterized by their altitude, which can be classified into three main groups according to the altitude: (1) high-level cloud consisting of ice-crystals, (2) mid-level cloud-primarily made of water droplets with ice-crystals, and (3) low-level cloud composed most of the water droplets. Therein, the optical signal is severely impacted by low-level clouds (less than 3 km). The reason behind is the Mie scattering phenomenon, i.e., the cloud droplet size is much larger than optical wavelength [16]. As a result, the optical signal power and visibility are decreased. As reported in [15], variable visibility, V, can be estimated as

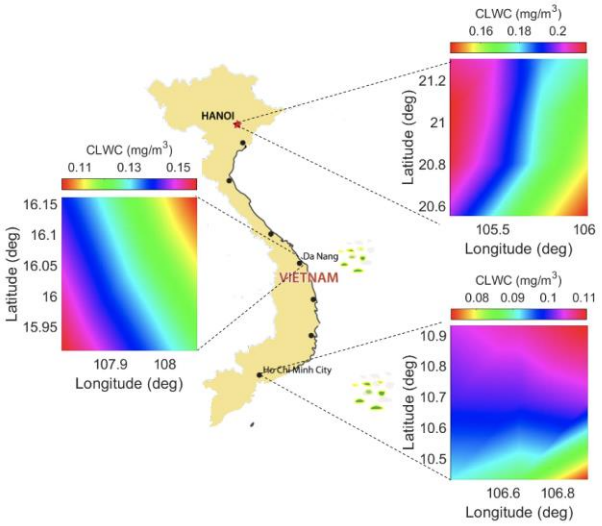

Fig. 2. Average CLWC of 5 years in Hanoi, Danang, Hochiminh.

$$V = \frac{1.002}{\left(W_c \times N_c\right)^{0.6473}}, \tag{1}$$

where $W_c\left(\text{g/m}^3\right)$ is the cloud liquid water content (CLWC), $N_c\left(\text{cm}^{-3}\right)$ is the cloud droplet number concentration, which depends on the cloud droplet radius, and it can be expressed as

$$N_c = \frac{3W_c}{4\pi r^3 \rho} \times 10^6, \tag{2}$$

where $\rho\left(=1\text{g/cm}^3\right)$ is the density of liquid water, and $r\left(\mu\text{m}\right)$ is the mean of cloud droplet radius which is given based on cloud types, e.g., Stratus $\left(r = 3.33\mu\text{m}\right)$, Altostratus $\left(r = 4.5\mu\text{m}\right)$ and Nimbostratus $\left(r = 4.7\mu\text{m}\right)$ [17].

According to [15], the log-normal distribution can be used to model the cloud attenuation accurately, the probability density function (PDF) is written as

$$f_{A_c}\left(A_c\right) = \frac{1}{\sqrt{2\pi}\sigma A_c}\exp\left[-\frac{\left(\ln A_c - \mu\right)^2}{2\sigma^2}\right], \tag{3}$$

where $A_c\left(\text{dB}\right)$ is the cloud attenuation. σ and μ are obtained based on the maximum likelihood estimation of the curve-fitting method.

B. Turbulence loss

Atmospheric turbulence is a random phenomenon due to the inhomogeneity in temperature and atmospheric pressure along the propagation path. As a result, the optical received power is strongly decreased by turbulence-induced fading. Typically, the turbulence strength is given by Rytov variance, denoted as σ_R^2, in which weak, moderate, and strong turbulence regimes corresponding to $\sigma_R^2 < 1$, $\sigma_R^2 \approx 1$, and $\sigma_R^2 > 1$[4]. In optical HAPS-based FSO systems, the Rytov variance in the case of plane wave propagation is given as

$$\sigma_R^2 = 2.25 k^{\frac{7}{6}} \sec^{\frac{11}{6}}(\theta) \int_{H_g}^{H_{hap}} C_n^2(h)\left(h-H_g\right)^{\frac{5}{6}} dh \tag{4}$$

where $k = 2\pi/\lambda$ is the wave number, θ is the HAP's zenith angle, H_g is the height of ground user (e.g., ground station, vehicle, etc.), and H_{hap} is the altitude of the HAP. In the vertical network, the computation of the atmospheric turbulence become more complex due to the altitude-dependent index structure parameter [9], which can be determined as

$$C_n^2(h) = 0.00594\left(\frac{v_{wind}}{27}\right)^2\left(10^{-5}h\right)\exp\left(-\frac{h}{1000}\right) + 2.7\times10^{-16}\exp\left(-\frac{h}{1500}\right) + C_n^2(0)\exp\left(-\frac{h}{100}\right) \tag{5}$$

Where $C_n^2(0)$ is the ground turbulence level varying in the range of $10^{-17}\,\mathrm{m}^{-2/3}$ (weak turbulence regime) to $10^{-13}\,\mathrm{m}^{-2/3}$ (strong turbulence regime), and v_{wind} (m/s) is the root mean squared wind speed with typical value of 21 m/s.

III. PERFORMANCE ANALYSIS

This section concentrates on the design of the power link margin for the HAPS-based FSO system. Notably, optical power loss is analyzed under the impact of clouds and atmospheric turbulence. The link availability is then derived to estimate the attenuation due to atmospheric-related issues. In addition, our solution, site diversity technique, is also proposed to improve the link availability.

A. *Power link budget*

The optical signal is vulnerable to atmospheric-related issues such as turbulence and clouds. To design the link budget for optical vertical framework, the power loss, denoted as A_{total}, owning to cloud attenuation and atmospheric turbulence, can be calculated as

$$A_{\mathrm{total}} = A_{\mathrm{c}} + A_{\mathrm{tur}} \tag{6}$$

where A_{c} and A_{tur} are the attenuation caused by clouds and atmospheric turbulence, respectively. Let d is the transmission distance from the HAP to end user on the ground, then, A_{tur} can be determined as

$$A_{\mathrm{tur}} = 4.343\left[\mathrm{erfcinv}\left(2p_{\mathrm{th}}\right)\sqrt{2\ln\left(\sigma_p^2+1\right)} - \frac{1}{2}\ln\left(\sigma_p^2+1\right)\right], \tag{7}$$

Where erfcinv(.) is the inverse error function, D is the receover aperture diameter, λ is optical wavelength, and $p_{\mathrm{th}} = 10^{-2}$ [18]. The power scintillation index can be given as

$$\sigma_p^2 = \sigma_R^2\left[1 + 0.33\left(\frac{\pi D^2}{2\lambda d}\right)^{\frac{5}{6}}\right]^{-\frac{7}{5}}. \tag{8}$$

Regarding the computation of the cloud attenuation, it is well investigated in [10] as followed

$$A_{\mathrm{c}} = \sum_{k=1}^{M} 4.343\left[\frac{3.91}{V_k}\left(\frac{\lambda[\mathrm{nm}]}{550}\right)^{-q_k}\right]\frac{\Delta h_k}{\sin(\varphi)}, \tag{9}$$

where M is the total cloud layers, e.g., 5 layers are considered in our work. V_k and Δh_k are the visibility and the vertical extent of the *k*-th layer, respectively. q_k is the Kim's model parameter and can be shown as

$$q_k = \begin{cases} 1.6 & \text{if } V_k > 50\text{ km}, \\ 1.3 & \text{if } 6\text{ km} < V_k \le 50\text{ km}, \\ 0.16V_k + 0.34 & \text{if } 1\text{ km} < V_k \le 6\text{ km}, \\ V - 0.5 & \text{if } 0.5\text{ km} < V_k \le 1\text{ km}, \\ 0 & \text{if } V_k \le 0.5\text{ km}. \end{cases}$$

B. *System availability*

A link availability is defined as the power budget more significant than the total loss caused by clouds and turbulence and can be estimated as

$$\begin{aligned} P_{\mathrm{avai}} &= \Pr\left(A_{\mathrm{total}} \le A_{\mathrm{budget}}\right) \\ &= \Pr\left(A_{\mathrm{c}} \le A_{\mathrm{budget}} - A_{\mathrm{tur}}\right) \end{aligned} \tag{10}$$

where A_{budget} (dB) is the total link budget, which is normally used to estimate before transmitting aim to achieve as much as possible link availability. Based on Eq. (3), and given $A_{\mathrm{th}}(\mathrm{dB}) = A_{\mathrm{budget}} - A_{\mathrm{tur}}$ the link availability is re-written as

$$\begin{aligned} P_{\mathrm{avai}} &= \int_0^{A_{\mathrm{th}}} f_{A_{\mathrm{c}}}\left(A_{\mathrm{c}}\right) dA_{\mathrm{c}} \\ &= \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left[\frac{\ln\left(A_{\mathrm{th}}\right) - \mu}{\sqrt{2}\sigma}\right] \end{aligned} \tag{11}$$

Where erf(.) is the error function, and ln(.) is the natural logarithm function. Therein, A_{th} is the cloud attenuation threshold. As defined in Eq. (10), the optical link between HAPS and end-user is not availability if the cloud attenuation is larger than threshold.

C. HAPS diversity

The site diversity is known as the technique to improve the link availability under the impact of cloud coverage and atmospheric turbulence. Assuming the number of HAPS is more than one at a specific location and the distance between two HAPS is far enough to avoid the cloud coverage. Let *N* is the total number of HAPS that are available for optical communications. By using assumption, the link availability is defined as at least one HAPS is available at any time and can be determined as

$$\begin{aligned} A &= 1-\prod_{i=1}^{N} \Pr\left[A_{\text{loss}}(i) > A_{\text{budget}}\right] \\ &= 1-\prod_{i=1}^{N} P_{\text{na}}(i), \end{aligned} \tag{12}$$

where $P_{\text{na}}(i)$ is defined as the probability that i-*th* HAPS is not available for communication at given time.

IV. NUMERICAL RESULTS

Numerical results of link availability in 6 years from 2015 to 2020 for several regions in Vietnam are presented in this section. The CLWC data are observed from the ERA-Interim database [14]. In particular, the average CLWC is collected with one sample per hour over a spatial resolution of $0.25^\circ \times 0.25^\circ$ latitude/longitude. We divide the cloud layer into five layers by considering the low-cloud layer with an altitude from 1 km to 3 km. The optical wavelength, $\lambda = 1550$ nm, HAPS zenith angle of 40°, HAPS altitude $H_{hap} = 20$ km, receiver aperture diameter $D = 10$ cm, and receiver altitude $H_g = 10$ m are used in this study.

First, we investigate the impact of clouds without considering the atmospheric turbulence. In this scenario, Fig. 3 illustrates the link availability for three big cities in Vietnam, including Hanoi, Danang, and Hochiminh, when the link budget for cloud attenuation is 30 dB. It is worth noting that the cloud coverage is different from areas and climate zones. In Vietnam, the division of seasons is well recognized in the North, e.g., the Hanoi capital. At the top of Fig. 3, we can see that system availability varies according to months (i.e., season variation). For instance, the HAPS-based FSO system availability is lowest during the rainy season (e.g., July, August, and September). In contrast, Danang and Hochiminh have two main seasons, including the rainy and dry seasons. In addition, the cloud, which is caused by condensation in the air, appears much more in the regions near the ocean, such as Danang. Here, the HAPS system's link availability is sometimes very low, such as in October with 78% availability. Besides, the rainy season lasts from May to the end of November in Hochiminh city. Hence, the availabilities of optical downlinks in these months are lower than in the other months.

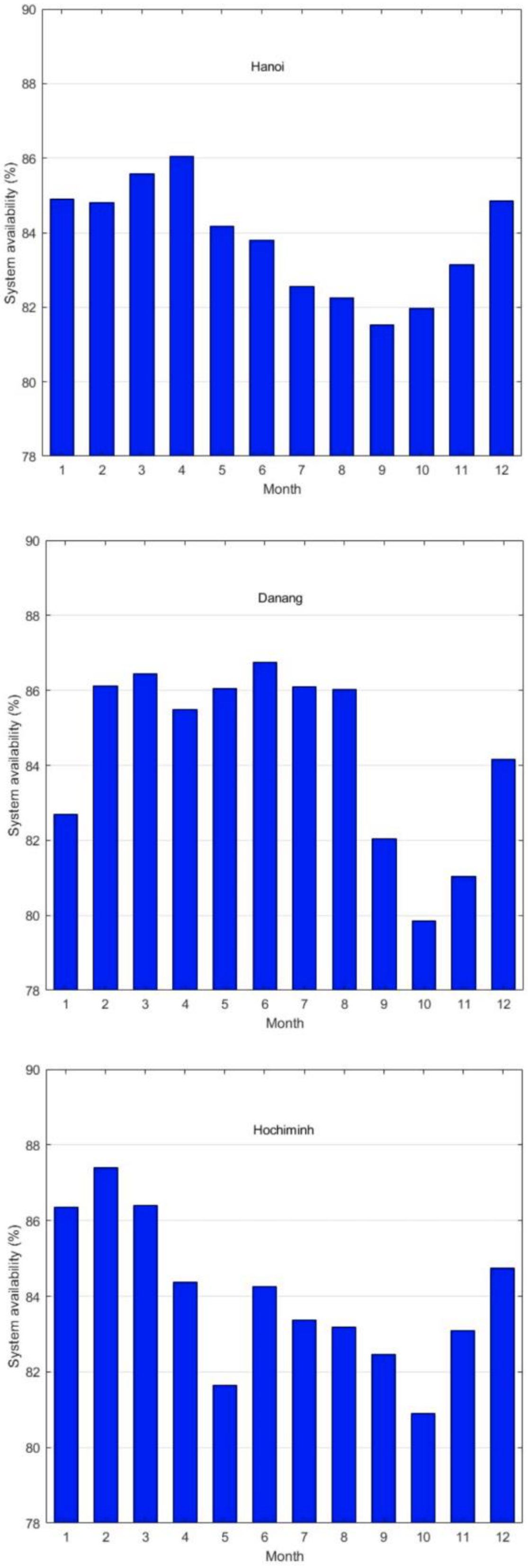

Fig. 3. HAPS-based FSO system availability in Hanoi (top), Danang (middle), and Hochiminh (bottom).

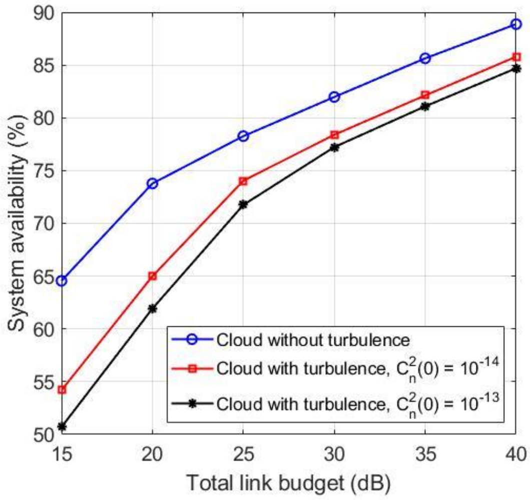

Fig. 4. HAPS-based FSO system availability in Hanoi during rainy season.

Next, Fig. 4 illustrates the link availability in Hanoi over the range of the total link budget with the joint impact of clouds and atmospheric turbulence. The total link budget is considered for both cloud attenuation and turbulence loss. As seen from the figure, the link availability has significantly deteriorated under the impact of the cloud combined with atmospheric turbulence. For example, the HAPS-based FSO system availability is 81.96%, 78.39%, and 77.25% respective to no turbulence, moderate turbulence, and strong turbulence.

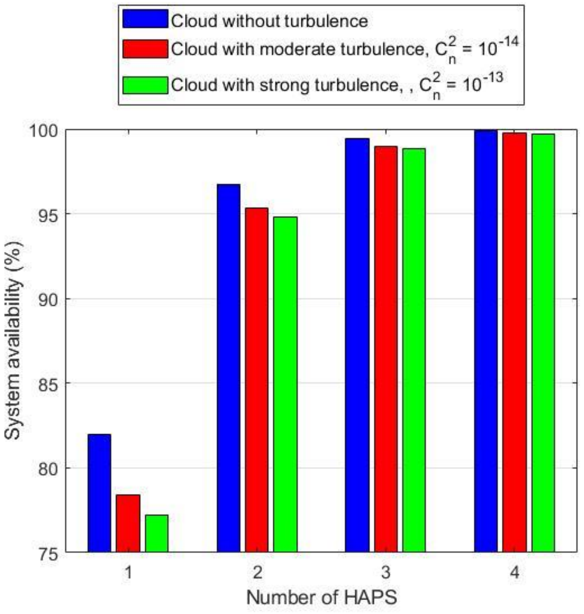

Fig. 2. System availability improvement by using HAPS diversity in Hanoi during rainy season.

Finally, a swarm of HAP (i.e., HAPS diversity) is proposed to improve the system availability. The advantage of the technique is highlighted in Fig. 5, with the total link budget of 30 dB. The system availability is much improved by deploying more than one HAPS. In particular, the HAPS-based FSO system availability can be achieved approximately 100% availability with the help of four HAPS simultaneously operation.

V. CONCLUSIONS

In this paper, HAPS-based FSO system availability has been investigated for several regions in Vietnam under the impact of cloud attenuation and atmospheric turbulence. The data was observed from 2015 to 2020 produced by reanalysis meteorological ECMWF ERA-5. The comprehensive numerical results were presented link availability under the above-mentioned challenging issues and validate the effectiveness of applying the site diversity technique.

Our study provides a primary method for analyzing the influence of weather conditions on wireless optical communication systems based on high-altitude platforms station. This analysis is not limited to the HAPS-based FSO system. Still, it can apply to other platforms such as GEO, MEO, LEO, or low-altitude drones (e.g., drones, helicopters, etc.). Besides, receivers are stationary ground stations and can also be applied to other vehicles, such as self-driving cars and high-speed trains. For future work, we plan to build a general wireless optical communication channel model to analyze the impact of weather conditions and other effects from the devices such as UAV-hovering misalignment, satellite vibration, etc.

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TÁC ĐỘNG CỦA MÂY VÀ NHIỄU LOẠN KHÍ QUYỂN ĐỐI VỚI HỆ THỐNG FSO DỰA TRÊN HAPS

***Tóm tắt* –** Bài báo này nghiên cứu tính khả dụng của hệ thống quang không dây (FSO) dựa trên trạm nền cao (HAPS), dựa trên dữ liệu đám mây quan sát được từ Trung tâm Dự báo Thời tiết Tầm trung Châu Âu (ECMWF). Dữ liệu thu thập được sau đó được sử dụng để đánh giá tính khả dụng của hệ thống thông tin quang cho một số vùng ở Việt Nam. Các kết quả cho thấy lợi ích của việc sử dụng phân tập trạm theo địa lý để chống lại sự suy hao do đám mây và nhiễu loạn khí quyển.

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