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Feasibility of FSO feeder links for drones exploiting COTS components

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***Abstract*—A key part of future Non-Terrestrial Networks are the low-altitude Unmanned Aerial Vehicles (UAVs), which can provide ad hoc connectivity in event coverage, emergency communication, and close monitoring. They need high-capacity bidirectional feeder links because of bandwidth-hungry applications and the UAV operation itself. We design the Free Space Optics (FSO) links for 1 Gb/s and 10 Gb/s speed, assuming Commercial Off-the-Shelf (COTS) components. The key impairments that a Gaussian beam experiences under atmospheric turbulence are investigated, including on-axis scintillation, beam wandering, and pointing errors, determining the corresponding effects on link reliability. The results show the feasibility of utilizing COTS components to implement the FSO feeder links in relevant scenarios.**

***Index Terms*—non-terrestrial network, unmanned aerial vehicles, free space optics, commercial off-the-shelf.**

I. Introduction

Unmanned Aerial Vehicles (UAVs) enhance Non-Terrestrial Networks (NTNs) by providing low-latency, flexible, and rapidly deployable communication support through dynamic low-altitude (100 m to 1 km) operations. Free Space Optics (FSO) communication is gaining popularity in UAV-based NTNs thanks to its possibility to achieve high data rates, low interference, and lightweight transceivers, making it an ideal alternative to radio frequency systems, especially for energy-constrained UAVs [1]. However, implementing FSO links in UAVs presents critical challenges such as mobility-induced misalignment, and atmospheric turbulence.

Several studies focused on integrating FSO links within dynamic UAVs network topologies. For instance, in [2], the feasibility and potential benefits of using FSO links with aerial platforms to create a vertical backhaul/fronthaul architecture for next-generation mobile networks are explored along with link budget analysis under varying weather and altitude at 45° elevations. In [3], a comprehensive theoretical framework was developed to model angular fluctuations caused by weak atmospheric turbulence and mechanical vibrations, introducing a novel statistical model that captures both small-angle and large-angle deviations. Finally, [4] presents a detailed channel model and analytical analysis accounting for the unique characteristics of a hovering UAV platform, including pointing error (PE), and potential beam wander (BW) under weak turbulence conditions.

Here, we provide a numerical analysis on using Commercial Off-the-Shelf (COTS) components to design cost-effective $1\,\mathrm{Gb/s}$ and $10\,\mathrm{Gb/s}$ bidirectional FSO feeder links for drones. Unlike previous studies, which focus on ideal conditions or weak turbulence, we evaluate system performance under realistic and harsh environmental conditions, including moderately hazy weather and strong atmospheric turbulence [5], a regime that remains largely underexplored in the context of drone-based FSO links. We also provide a comparison with the weak turbulence scenario to highlight performance differences. Noteworthy, we intentionally avoid the implementation of complex Adaptive Optics (AO) and instead leverage only a simpler Tip and Tilt (TT) mechanism to correct for lower-order aberrations. This simplification dramatically reduces the cost and complexity, while still maintaining robust link performance by appling a divergence control strategy that mitigates pointing errors due to turbulence and drone motion. To our knowledge, this is the first complete numerical approach to evaluate the feasibility of high-data-rate drone-based FSO links under strong turbulence using only TT correction, offering a practical and bit rate scalable solution for next-generation aerial communication networks.

II. System Scenario of Communication

The considered scenario is presented in Fig. 1. A drone is positioned 1 km above sea level and it serves as a mobile base station to boost network capacity during events or to provide emergency communication in disaster zones, i.e., when ground networks are overloaded or unusable. The drone is equipped with sub-6 GHz wireless communication systems, which are commonly used in current cellular networks due to their reliable coverage and ability to penetrate obstacles. These systems enable the drone to establish service links directly with ground users, allowing it to function as an aerial base station or relay. For the bidirectional backhaul, the drone uses a FSO link with the nearest Optical Ground Station (OGS), enabling high-capacity data transmission by aggregating the traffic collected from users and relaying it to the core network via the OGS, ensuring end-to-end data delivery.

The system can operate under challenging environmental conditions in moderately hazy weather (visibility 5 km), and strong atmospheric turbulence, i.e., refractive index structure parameter $C_n^2(0) = 1.7 \times 10^{-13}\,\mathrm{m}^{-\frac{2}{3}}$ and with a wind speed of 32.5 km/h at OGS level. Therefore, the optical beam experiences significant atmospheric effects during propagation

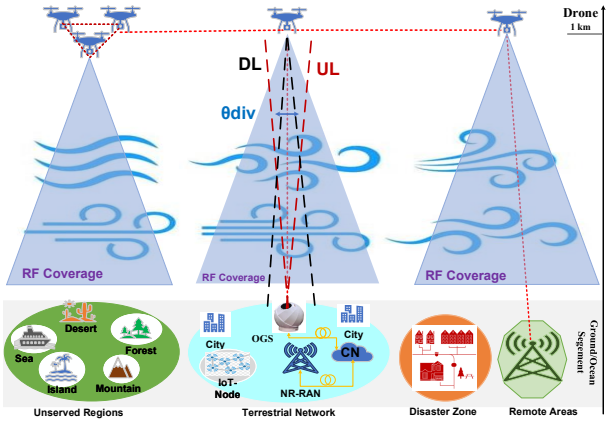

Fig. 1: A scenario depicting communication between an OGS and a Drone, CN: Core Network, NR-RAN:Radio Access Network.

in either Uplink (UL) (i.e., OGS to drone) or Downlink (DL) (i.e., drone to OGS). A summary of the considered weather and atmospheric parameters is presented in Table I. In the same table, we also report the values of the spatial (Fried coherence length r_0) and temporal (Greenwood frequency f_g) parameters [5], at 30° and 90°. As expected, strong turbulence exhibits lower r_0 and higher f_g compared to weak turbulence conditions.

The considered FSO system is designed by implementing COTS components for cost-effectiveness and ease of deployment. Both drone and OGS are equipped with a simple, yet robust, intensity modulation/direct detection [6] commercially available transceivers. They are developed for terrestrial networks operating at 1550 nm. The system supports either 1 Gb/s or 10 Gb/s non-return-to-zero data transmission using robust On-Off Keying (OOK) modulation. A COTS erbium-doped fiber amplifier with 17 dBm (50 mW) output power boosts the signal power (P_T) at the Transmitter (TX) telescope. Due to the combined effects of atmospheric turbulence and drone mobility, precise pointing accuracy becomes a significant challenge in FSO links. Here, we consider a tracking mechanism with a realistic UAV pointing error of 300 µrad [7]. A controlled beam divergence of 1465 µrad (compatible with telescope size of 4 cm) is considered to reduce the complexity of alignment under adverse conditions. Although this increases path loss, it strongly enhances the resilience against pointing errors caused by atmospheric effects (i.e., BW), drone movement and vibrations. During propagation, the optical beam is affected by attenuation due to haze and by phase distortions due to atmospheric turbulence, leading to power fluctuations at the receiver. A Receiver (RX) telescope (D_R) of 4 cm captures the incoming signal. It is important to note that using a larger RX telescope on OGS (or drone) can capture more signal, thereby increasing the received power (P_R). However, in the case of a drone, this also adds significant weight and requires high-power gimbals, which can severely affect flight time and energy efficiency. Therefore, a balance between performance and payload constraints is essential.

TABLE I: Considered atmospheric conditions

Atmospheric Conditions			Atmospheric Parameters			
			30°		90°	
Turbulence	$C_n^2(0)$ ($m^{-2/3}$)	Wind speed at OGS (km/h)	f_g (Hz)	r_0 (cm)	f_g (Hz)	r_0 (cm)
Strong	1.7×10^{-13}	32.4	125.8	3.7	80.1	5.7
Weak	5×10^{-14}	10.8	25.5	13.3	10.2	21.3

To determine P_R, we used the well known formula [8]:

$$P_R|_{dB} = P_T + G_{TX} + G_{RX} + 2L_\eta + L_{FSO} + L_{ATM} + L_S + L_{BW} + L_P + L_{FC}. \quad (1)$$

where G_{TX} and G_{RX} are the TX and RX telescope gains, with optimal beam truncation [8]. We assume a telescope optical loss L_η of 50 % to realistically account for practical losses from lens imperfections, misalignment, and internal optical components, both at TX and RX sides. Free space loss L_{FSO} is the dominant propagation loss, it is mainly caused by the diffraction limited spreading [9]. Under moderate haze with 5 km visibility, Mie scattering dominates at 1550 nm, resulting in an atmospheric loss L_{ATM} [8]. The scintillation loss L_S is estimated using the Gamma-Gamma distribution, as it accurately captures the combined impact of both small-scale (scattering) and large-scale (refraction) turbulence [8]. Then L_{BW} presents the BW loss arising from lower-order wavefront aberrations. A TT correction is used at the OGS: it performs wavefront pre-correction on the UL beam based on the DL signal, significantly reducing the angle of arrival fluctuations at the RX. This correction improves the signal stability and enhances the overall link performance. Here, anisoplanatism can be neglected as the UAV can be considered quasi-static at 1 km. Beta distribution is used to estimate L_{BW}, as it accurately captures the bounded and skewed nature of these displacements [8]. L_P presents the PE loss due to the combined effect of drone hovering and mechanical vibration; this is also estimated by the beta distribution [8]. L_S, L_{BW}, and L_P are determined at 0.1 % fading probability, which is the safety allowance to compensate for intensity fluctuations caused by the atmospheric turbulence and ensure a reliable connection for 99.9 % of the time. Finally, L_{FC} caused by turbulence induces wavefront distortions (and therefore, fiber coupling) is estimated using the method described in [10].

In the optical communication system, the link is considered reliable when P_R exceeds the RX sensitivity P_S, which is the minimum power level required for the RX to correctly detect and decode the incoming signal with an acceptable Bit Error Rate (BER). The P_S is set at a pre-forward error correction (Pre-FEC) BER of 10^{-3}, the typical threshold for Reed-Solomon in OOK to ensure near error-free communication. If P_R drops below P_S, due to fading events, link quality deteriorates, leading to increased BER or possible link failure. Therefore, maintaining a positive power margin ($P_R > P_S$) is critical to reliable communication, especially under strongly varying environmental conditions. This Link Margin (LM) is assessed using $\mathrm{LM(dB)} = P_R - P_S$.

TABLE II: Summary of link budget estimations

UL/DL	OGS-to-Drone				Drone-to-OGS			
Regime	Weak		Strong		Weak		Strong	
Elevation Angle	30°	90°	30°	90°	30°	90°	30°	90°
G_T (dB)	65.2		65.2		65.2		65.2	
G_R(dB)	98.2		98.2		98.2		98.2	
L_{FSO}(dB)	-204.2	-198.2	-204.2	-198.2	-204.2	-198.2	-204.2	-198.2
L_{ATM}(dB)	-2	-1	-2	-1	-2	-1	-2	-1
L_S(dB)	-4	-1.3	-9.2	-4	-2.9	-1	-4.3	-1.3
L_{BW}(dB)	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.1	-0.1
L_P(dB)	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1	-5.1
L_{FC}(dB)	-3	-3	-3	-3	-3	-3	-5.9	-3.5

III. Results and Feasibility Analysis

This section presents the results of the numerical analysis of the link budget for $1\,\mathrm{Gb/s}$ and $10\,\mathrm{Gb/s}$ FSO feeder links, considering elevation angles from 30° to 90° between drone and OGS. For convenience, a summary of the link budget analysis is presented in Table II for elevation angles of 30° and 90° in weak and strong turbulence regimes. The data demonstrate that turbulence strength and elevation angle critically impact the link performance, with strong turbulence causing greater losses and requiring larger margins to maintain reliability, especially at lower elevations.

In detail, we control the beam divergence to 1465 µrad, which is over four times larger than the pointing error of 300 µrad. This ensures the system remains robust against pointing inaccuracies. As a result, the transmitter gain ($G_T = 65.2\,\mathrm{dB}$) is quite smaller than the receiver gain ($G_R = 98.2\,\mathrm{dB}$) for the 4 cm telescope. These gain values are the same for each considered condition (i.e. atmospheric turbulence, elevation angles…). In contrast, L_{FSO} changes according to the elevation angles, because the slant distance between the OGS and the drone increases as the elevation angle decreases, resulting in a longer transmission path. For 30°, the propagation distance of the beam is 2 km; this gives −204 dB loss, whereas at elevation 90° the propagation distance is 1 km, contributing for 6 dB lower loss. At fading probability of 0.1 %, L_S, and L_{BW}, specifically higher-order and lower-order aberrations, are much more severe in strong atmospheric turbulence compared to weak turbulence. Moreover, the UL is more affected by turbulence than the DL beam as the UL beam encounters the most turbulent regions near the OGS immediately upon transmission, while the DL beam pass through less turbulent regions before reaching the ground. As a result, L_S and L_{BW} vary based on turbulence regimes, elevation angles, and directions. The low L_{BW} values are achieved thanks to the careful selection of a high beam divergence, which reduces the beam wander effect in both link directions. L_P also benefits from this choice, resulting in a pointing loss of the tracking system that remains constant at −5.1 dB across all turbulence regimes, elevation angles, and link directions, based on the residual pointing error caused by turbulence and UAV instability.

Aside from the DL beam under strong turbulence conditions, L_{FC} consistently remains around −3 dB in both weak and strong turbulence regimes for both directions. This consistency is attributed to the atmospheric coherence length r_0 being larger than the effective aperture to D_R. When $D_R < r_0$, the incoming wavefront remains relatively undistorted over the aperture, efficiently coupling of the received optical signal into the single-mode fiber. This is the condition encountered in weak turbulence, where $r_0 = 13.3\,\mathrm{cm}$, larger than D_R. In contrast, due to strong atmospheric turbulence near the ground the r_0 is 3.7 cm in DL, comparable to D_R reducing the coupling efficiency below 50 %. Using a larger D_R compared to r_0 can help mitigate the scintillation thanks to aperture averaging; however, it also increases wavefront distortion and the fiber coupling loss. To address this issue, AO is needed at the OGS to correct for the higher-order aberrations, which adds complexity and cost of the system. Therefore, selecting an appropriate RX size is crucial to avoid the need for AO, especially for UAV-based links where simplicity and cost-effectiveness are critical. Finally, P_R is calculated and compared with P_S= −55 dBm for 1 Gb/s and P_S= −45 dBm for 10 Gb/s at a pre-FEC BER of 10^{-3}. When P_R exceeds P_S, it confirms that the FSO links are feasible and reliable for drone communication.

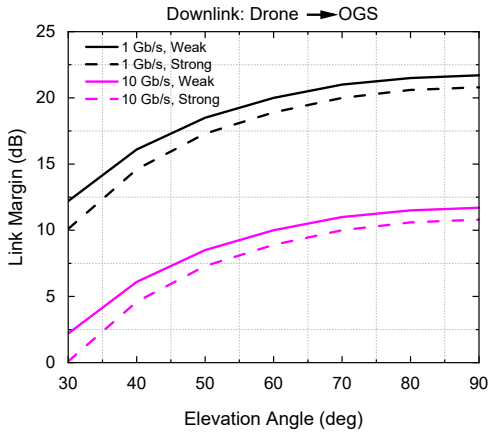

Fig. 2: Estimated link margins for FSO DL under strong and weak turbulence conditions at two link capacities (1 Gb/s-OOK and 10 Gb/s-OOK).

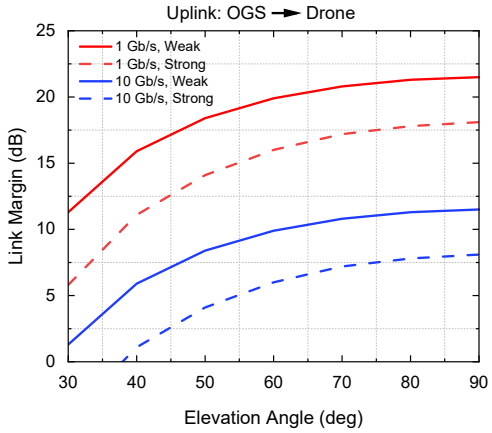

Fig. 3: Estimated link margins FSO UL under strong and weak turbulence conditions at 1 Gb/s-OOK and 10 Gb/s-OOK.

Figures 2 and 3 present the calculated LM (in dB) for UL and DL respectively. This LM is reported as function of

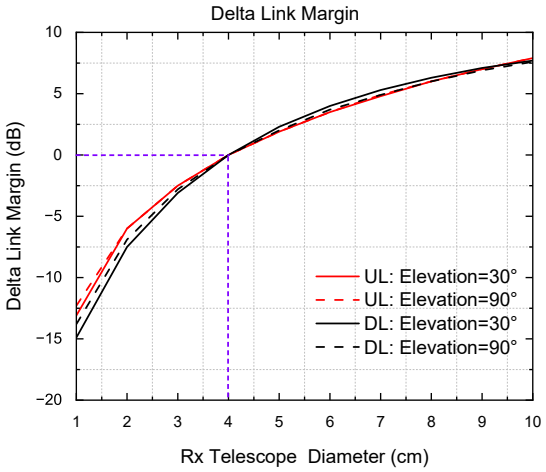

Fig. 4: Delta link margin at different RX telescope diameters

varying elevation angles (30° to 90°), for both 1 Gb/s and 10 Gb/s data rates, under strong and weak turbulence. The solid lines represent weak turbulence, while the dashed lines represent strong turbulence. As expected, LMs are consistently higher under weak turbulence due to a lower impact of the impairments, reaching up to over 20 dB, while 10 Gb/s links show lower margins, especially under strong turbulence, with margins dropping close to 0 dB at low elevation angles (30°). For both data rates, the LM increases with elevation angle, since higher angles correspond to shorter atmospheric paths and lower attenuation. Despite the effects of strong turbulence, all scenarios maintain positive LMs – except 10 Gb/s at 30° – demonstrating the feasibility of maintaining reliable DL and UL FSO communication even under challenging atmospheric conditions.

Finally, we keep the divergence of the TX beam constant and calculate how the LM varies with the RX telescope diameter, referred to as the Delta Link Margin (DLM). Results are presented in Fig. 4. The curves were computed based on strong turbulence; however, similar curves can also be obtained in weak condition. The DLM is measured relative to the baseline case at a 4 cm RX diameter, indicated by the dashed purple line. As the RX diameter increases from 1 cm to 10 cm, the DLM improves from approximately −15 dB to 7.7 dB. This trend shows that larger RX diameters enhance the LM. As the RX diameter increases, three key parameters are affected: G_R, L_S, and L_{FC}. Specifically, G_R increases at larger diameters; L_S reduce thanks to aperture averaging, especially under strong turbulence. On the other hand, L_{FC} tends to increase with RX diameter, as a larger aperture captures more turbulent patches. If the RX diameter lower than 4 cm, the LM will reduce by around −5 dB with only 1 cm difference diameter, because the resultant impact of the lower G_R and higher L_S is dominant over L_{FC} in the LM estimation. From 4 cm to 10 cm, the improvement of G_R and L_S counterbalances the negative effect L_{FC}, resulting in higher DLM compared to 4 cm. For instance, at 8 cm, this provides around 5 dB more margin than the considered 4 cm. Therefore, the challenges of the 10 Gb/s link at 30° (in both directions, as presented Fig. 2 and Fig. 3) can be overcome. In summary, Fig. 4 offers a guide for selecting an RX diameter, but practical considerations regarding SWaP requirements must also be taken into account.

IV. Conclusion

We provided a first comprehensive evaluation of COTS-based FSO feeder links for drone communications at 1 Gb/s and 10 Gb/s. We considered a wide range of elevation angles 30 – 90° under realistic and challenging atmospheric conditions. We strategically chose wide beam divergence to reduce the pointing errors and selected a small RX telescope diameter to minimize the drone weight, size, and power usage, as well as avoid the need for AO at OGS, thereby strongly simplifying the system deployment. The results highlight the capability of COTS components to maintain a robust communication even under strong turbulence and moderate haze, except at 10 Gb/s in 30°. However, the increased LM observed at higher elevation angles demonstrates the system ability to withstand greater losses, indicating its robustness in even more challenging conditions. Overall, the study demonstrates the potential of COTS-based FSO links for future NTNs, particularly for high-reliability drone connectivity.

Acknowledgments

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