

A Weather-Dependent Hybrid RF/FSO Satellite Communication for Improved Power Efficiency

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Abstract—Recent studies have shown that satellite communication (SatCom) will have a fundamental role in the next generation non-terrestrial networks (NTN). In SatCom, radio frequency (RF) or free-space optical (FSO) communications can be used depending on the communication environment. Motivated by the complementary nature of RF and FSO communication, we propose a hybrid RF/FSO transmission strategy for SatCom, where the satellite selects RF or FSO links depending on the weather conditions obtained from sensors and used for the context-awareness. To quantify the performance of the proposed network, we derive the outage probability (OP) expressions by considering different weather conditions. Moreover, asymptotic analysis is conducted to obtain the diversity order. Furthermore, we investigate the impact of non-zero boresight pointing errors and illustrate the benefits of the aperture averaging to mitigate the effect of misalignment and atmospheric turbulence. Finally, we suggest effective design guidelines that can be useful for system designers. The results have shown that the proposed strategy performs better than the dual-mode conventional hybrid RF/FSO communication in terms of OP offering some power gain.

Index Terms—Hybrid radio frequency (RF)/free-space optical (FSO), outage probability, satellite communication.

I. INTRODUCTION

NEXT-GENERATION communication networks will integrate space communication with terrestrial infrastructure for heterogeneous networks. In the near future, low Earth orbit (LEO) satellites, which are able to cross over the continents within a few minutes, are expected to play a key role in the next generation networks, due to their intrinsic features. LEO satellites introduce agility to the network and enable high throughput broadband services with low latency [1].

To address the traffic demand of these services, the use of free-space optical (FSO) communication has attracted considerable attention from both the research community and

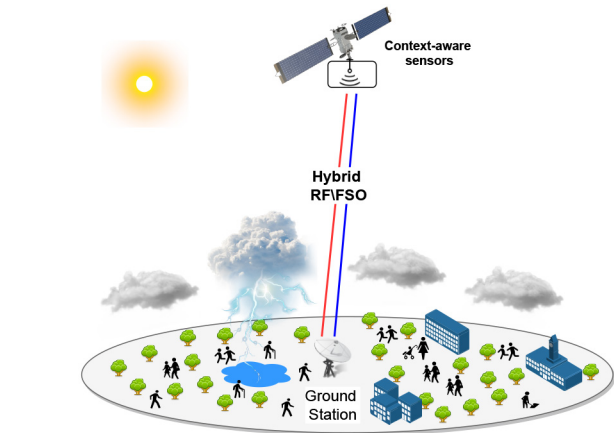


Fig. 1. Illustration of weather-dependent hybrid RF/FSO SatCom.

industry for satellite communication (SatCom) networks. In fact, the FSO technology provides several advantages such as high data rates, high bandwidth, and low cost [2].

Furthermore, FSO communication requires perfect line-of-sight (LOS) connectivity due to its narrow transmit bandwidth. Despite its great potential, FSO communication can experience reliability and availability issues due to atmospheric turbulence-induced fading, and sensitivity due to weather conditions including dense clouds, fog, and snow [3]. However, the impact of rain on FSO transmission is less significant compared to fog. Another major impairment for FSO links is the pointing error, which implies the possible displacement of the beams due to large distances, wind, pressure, and temperature variations [4]. Thereby, several techniques have been proposed in the literature to mitigate these adverse effects [5]. The use of radio frequency (RF) and FSO technologies together is an attractive solution to address this gap [6]. This combination consists of two possible configurations. The first one is the so-called mixed RF/FSO, in which RF communication is used at one hop and FSO communication at the other in a dual-hop or relay-assisted networks [6], [7]. The second combination is hybrid RF/FSO communication, in which RF link is incorporated in parallel with FSO link. In fact, the FSO and RF links are sensitive to non-overlapping conditions and considered to have a complementary nature [8]. So far, different approaches have been proposed in this context by considering soft-switching or hard-switching techniques [9]. In soft-switching, both links might be active depending on their availability, whereas in hard-switching, only one link can be active at a certain time. In the current literature, only a few

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papers have investigated hybrid RF/FSO communication for satellite systems [10-13] and, neither of them investigated the practical effects of weather conditions. Furthermore, pointing error, which is a critical metric in FSO communication, is barely investigated in hybrid RF/FSO configuration.

Different from the current literature, we provide a reliable communication strategy for the downlink SatCom by using hybrid RF/FSO communication considering soft-switching technique according to weather characteristics. More precisely, the proposed strategy enables us to switch between RF and FSO links depending on the weather conditions which can be obtained from the sensors on the satellite and used for the context-awareness. In this concept, we assume that the satellite detectors are able to scan the weather conditions of the atmosphere within the LOS continuously. Then, based on the extracted information, the satellite determines to activate the most favorable channel immediately. By doing so, the overall performance of the proposed scheme can be enhanced as the LEO satellite is aware of the weather conditions. For the proposed setup, FSO communication is modeled with exponentiated Weibull (EW) fading as it provides a better fit than all other models for different aperture sizes [14], whereas shadowed-Rician distribution is used to model the RF communication. Furthermore, we study the effect of atmospheric turbulence, scattering, and non-zero boresight pointing errors, and consider the impact of shadowing on communication performance. We also highlight the impact of aperture averaging to mitigate the effect of turbulence-induced fading and the misalignment of the transmitting beam to achieve better directivity. Outage probability (OP) expressions are derived for the proposed configuration. In addition, an asymptotic performance analysis is conducted and the achievable diversity gain is obtained. Finally, we compare our proposed strategy with the conventional dual-mode RF/FSO soft-switching communication and provide interesting design guidelines.

The remainder of this letter is organized as follows. Signals and system models are presented in the following section. In Section III, our proposed scheme is presented and the expressions of OP are derived. Numerical results are outlined and discussed followed by some design guidelines in Section IV, and Section V concludes this letter.

II. SIGNALS AND SYSTEM MODEL

In this letter, we consider a downlink SatCom, where an LEO satellite aims to communicate with a ground station (GS) where both RF and FSO channels are used in parallel to transmit identical rate information, based on their availability as shown in Fig. 1. More precisely, the LEO satellite, which is deployed with context-aware by the measurements of sensors, can detect the weather conditions on the ground continuously and adapt to the situation immediately. Thereafter, it uses the most favorable channel or both channels at the same time to transmit the information and accordingly adapts the transmission power. In the state where both channels are activated, the received signals are combined at the GS using the selection combining (SC) technique to maximize the overall performance. Although the maximum ratio combining (MRC) technique provides better performance, we consider SC due to its practical relevance. Table I summarizes the proposed

TABLE I
PROPOSED SCHEME

State (k)	Description	Observation	Transmission strategy
0	Thin Cloud	Both FSO and RF channels exhibit a higher performance	Dual (SC)
1	Rain	Only the FSO communication is favorable with full power	FSO
2	Fog	Only the RF channel is available with full power	RF

scheme. The signal models for both channels are given in the following subsections.

A. FSO Channel

The received optical signal¹ detected by the photodetector of the GS is modeled as $y = \zeta \sqrt{P_1} I x + n$. $0 \leq \zeta \leq 1$ denotes the optical-to-electrical conversion coefficient, P_1 is the transmit power of the satellite through the FSO link, I indicates the irradiance of the channel where $I = I^t I^p I^a$, where I^t indicates the atmospheric turbulence-induced fading [16], I^p is the pointing error and, I^a defines the atmospheric attenuation that includes Mie scattering and geometrical scattering [16, eq. (10)]. x is the transmitted signal and n is the zero-mean additive white Gaussian noise with one-sided power spectral density N_0 . In clear weather conditions, the geometrical scattering is mainly caused by thin cirrus clouds, and the attenuation coefficient is expressed as given in [16, eq. (8)], whereas under rainy conditions, the extinction coefficient can be expressed as $\Theta = 1.067 \mathcal{R}^{0.67}$ [9], where $\mathcal{R}$ is the rainfall rate in (mm/h). Thus, the instantaneous signal-to-noise ratio (SNR) at GS can be expressed as

$$\gamma_{FSO} = \frac{\zeta P_1 I^2}{N_0} = \bar{\gamma}_{FSO} I^2, \quad (1)$$

where $\bar{\gamma}_{FSO} = \frac{\zeta P_1}{N_0}$ is the average SNR of the FSO link and $\mathbb{E}[I^2] = 1$. In FSO communication, we consider the combined effects of atmospheric turbulence, non-zero boresight error and jitter. Thereby, the cumulative distribution function (CDF) of I can be given as [17]

$$F_I(I) = \frac{\alpha g^2}{\beta} \exp\left(-\frac{s^2}{2\sigma_s^2}\right) \sum_{i=0}^{\infty} \frac{(-1)^i \Gamma(\alpha)}{(1+i)! \Gamma(\alpha-i)} \\ \times \sum_{j=0}^{\infty} \frac{\left(\frac{s^2 g^2}{2\sigma_s^2 \beta}\right)^j}{j!} G_{j+2,1}^{j+2,1} \left(T_3(i) \left| \begin{matrix} \overbrace{1, T_1+1, \dots, T_1+1}^{(j+1)\text{terms}} \\ \underbrace{1, T_1, \dots, T_1, 0}_{(j+1)\text{terms}} \end{matrix} \right. \right), \quad (2)$$

where α, β denote the shape parameters [14], $g = w_{eq}/(2\sigma_s)$ is the ratio between the equivalent beam which is given as $w_{eq}^2 = w_z^2 \sqrt{\pi} \text{erf}(v)/(2ve^{-v^2})$ and the jitter standard deviation σ_s, η is the scale parameter [14], s presents the boresight

¹For FSO transmission, we consider intensity modulated direct detection (IM/DD) as it is largely used in practical urban networks owing to its simplicity and low cost [15].

value, $T_3(i) = (1+i)[\frac{I}{(\eta A_0)}]^\beta$ with $A_0 = [\text{erf}(v)]^2$ is the gathered optical power for zero difference between the optical spot center and the detector center, and $\text{erf}(\cdot)$ is the error function. Moreover, $v = \sqrt{\pi/2}a/w_z$ is the ratio of the aperture radius a and the beam-width w_z at the distance z with $w_z = \theta z$, where θ denotes the transmit divergence angle, and $T_1 = g^2/\beta$ [18]. Finally, $\Gamma(\cdot)$ is the Gamma function and $G_{p,q}^{m,n}\left(x \middle| \begin{smallmatrix} a_1, \dots, a_p \\ b_1, \dots, b_q \end{smallmatrix}\right)$ is the Meijer G-function [19].

In the absence of pointing errors, the CDF of I is given as [16, eq. (12)]. The parameters α , β , and η depend on the zenith angle of the satellite ξ , the wind speed level v_g expressed in m/s, the wavelength λ , the refractive index C_n^2 , and the aperture diameter D_G [16].

B. RF Channel

Let x denote the transmitted signal with power P_2 from the satellite to the GS through the RF link. The received signal at GS can be expressed as $y = \sqrt{P_2 h_l} h x + n$. h denotes the channel response of the path from the satellite to the GS that follows the shadowed-Rician fading [20], h_l is the path loss modeled as $h_l[\text{dB}] = G_T + G_R - 20 \log_{10}(\frac{4\pi L}{f}) - \omega_{oxy}L - \omega_{rain}L$ [9], where G_T and G_R are the gains of the transmitting and receiving antennas respectively, f is the RF wavelength, L is the propagation distance in km, ω_{oxy} , ω_{rain} are the attenuation coefficients due to the oxygen and rain scattering respectively [5], and n is the additive white Gaussian noise (AWGN) with one-sided power spectral density N_0 . Therefore, the instantaneous SNR at the GS can be written as

$$\gamma_{RF} = \frac{P_2 h_l |h|^2}{N_0} = \bar{\gamma}_{RF} |h|^2, \quad (3)$$

where $\bar{\gamma}_{RF} = \frac{P_2 h_l}{N_0}$ indicates the average SNR of the RF link with $\mathbb{E}[|h|^2] = 1$.

The main attenuation factor for the RF communication is the rain, where it rises linearly with the rainfall rate. Thus, the rain attenuation coefficient ω_{rain} (dB/km) can be expressed based on the rain rate $\mathcal{R}$ as $\omega_{rain} = k_r \mathcal{R}^\varrho$, where k_r and ϱ depend on the channel frequency f [21]. The CDF of the squared envelope of shadowed-Rician channel $|h|^2$ can be expressed as [22]

$$F_{|h|^2}(h) = \mu h \Phi_2(1-m, m; 2; -\nu h, -\vartheta h), \quad (4)$$

where $\mu = \frac{1}{2b}(\frac{2bm}{2bm+\Omega})^m$, with m representing the Nakagami-m severity parameter of the corresponding link and Ω and $2b$ are the average power of the LOS component and multipath component, $\nu = \frac{1}{2b}$, and $\vartheta = \frac{m}{2bm+\Omega}$. Finally, Φ_2 is the bivariate confluent hypergeometric function defined in [23, Sec. 9.26].

III. PERFORMANCE ANALYSIS

In this letter, we propose a new scheme in which an LEO satellite adapts its power and switches between RF and FSO links depending on the weather conditions obtained from the satellite sensors as shown in Table I. To this end, the overall system performance can be improved. Considering P_t is the

total transmit power of the satellite, we allocate equal transmit power on both RF and FSO links where $P_1 = P_2 = P_t/2$ when both links are used as given in State-0. However, a power allocation scheme can be adopted here to adjust the power levels if needed. For this state, we assume clear weather conditions (thin cloud), where both RF and FSO channels provide higher performance. For State-1, we consider the presence of heavy rain, which strongly affects the RF transmission and has fewer effects on FSO transmission. Thus, the RF link is not suitable for transmission, and the communication is conducted through the FSO link using the total transmit power is $P_1 = P_t$. Likewise, in State-2, we consider that FSO is totally unavailable due to heavy fog and the RF transmission is activated using the total transmit power $P_2 = P_t$. Furthermore, we denote the probability of occurrence of each state by p_k for $k \in \{0, 1, 2\}$.

A. Outage Probability

To study the performance of our proposed scheme, we derive the OP expressions. The OP can be defined as the probability that the instantaneous SNR γ falls below a predefined threshold γ_{th} and it can be written for the k -th state as $P_{out,k}(\gamma_{th}) = \Pr[\gamma \leq \gamma_{th}]$ for $k \in \{0, 1, 2\}$. For State-0, where both RF and FSO links might be active simultaneously, the GS uses SC. Thus, the final expression of OP for State-0 in the absence of pointing errors can be obtained as²

$$P_{out,0}(\gamma_{th}) = \sum_{\rho=0}^{\infty} \binom{\alpha}{\rho} (-1)^\rho \exp \left[-\rho \left(\frac{\gamma_{th}}{\eta^2 \frac{P_1(I^a)^2}{N_0}} \right)^{\frac{\beta}{2}} \right] \times \left(1 - \sum_{p=0}^{m-1} \sum_{q=0}^p \frac{\mu(1-m)_p (-\delta)^p}{q! \phi^{p-q+1} (\frac{P_2 h_l}{N_0})^{p+1} p!} \gamma_{th}^q \exp(-\phi \gamma_{th}) \right), \quad (5)$$

where $(\cdot)_p$ is the Pochhammer symbol, $\delta = \frac{\Omega}{2b(2bm+\Omega)}$, and $\phi = \frac{\nu-\delta}{\bar{\gamma}_{RF}}$ [24]. In the presence of non-zero boresight pointing errors, the OP for State-0 can be easily derived. On the contrary, the OP expressions for State-1 and State-2 can be simply obtained from their CDFs by using $P_{out}(\gamma_{th}) = F(\gamma_{th})$. In the presence of non-zero boresight pointing errors in State-1, the OP can be expressed as

$$P_{out,1}(\gamma_{th}) = \frac{\alpha g^2}{\beta} \exp(-\frac{s^2}{2\sigma_s^2}) \sum_{i=0}^{\infty} \frac{(-1)^i \Gamma(\alpha)}{(1+i)! \Gamma(\alpha-i)} \times \sum_{j=0}^{\infty} \frac{(\frac{s^2 g^2}{2\sigma_s^2 \beta})^j}{j!} G_{j+2,j+3}^{j+2,1} \left(T'_3(i) \middle| \begin{smallmatrix} (j+1)\text{terms} \\ 1, T_1+1, \dots, T_1+1 \\ 1, T_1, \dots, T_1, 0 \\ (j+1)\text{terms} \end{smallmatrix} \right), \quad (6)$$

where $T'_3(i) = (1+i)(\frac{1}{\eta A_0} \sqrt{\frac{\gamma_{th}}{P_t(I^a)^2/N_0}})^\beta$.³ In the absence of pointing errors, the OP expression for State-1 can be given

²The infinite summation in (5) converges very fast after 5 to 10 iterations with 10^{-6} convergence error.

³The double infinite summations, require 3 to 5 terms to converge with a convergence error 2×10^{-7} .

similarly to [16, eq. (23)]. For State-2, the OP is given as

$$P_{out,2}(\gamma_{th}) = 1 - \sum_{p=0}^{m-1} \sum_{q=0}^p \frac{\mu(1-m)_p(-\delta)^p}{q! \phi^{p-q+1} \left(\frac{P_t h_l}{N_0}\right)^{p+1} p!} \gamma_{th}^q \exp(-\phi \gamma_{th}). \quad (7)$$

Finally, the average performance of our proposed model can be given as $P_{out}(\gamma_{th}) = \sum_{k=0}^2 p_k P_{out,k}(\gamma_{th})$.

B. High SNR Analysis

In this subsection, we focus on the high SNR analysis and obtain the diversity order to gain more insights into the system behavior. The diversity order defines the slope of the OP versus the average SNR at asymptotically high SNR [7]. To do so, for FSO transmission in the absence of pointing errors, we apply $\exp(-x/a) \simeq 1 - x/a$ into the CDF of EW fading given in [16]. Thus, after a few manipulations, the asymptotic OP can be obtained as

$$P_{out,1}^\infty = \left[\left(\frac{\gamma_{th}}{(\eta I^a)^2} \right)^{\frac{\alpha\beta}{2}} \right] \left(\frac{1}{P_t/N_0} \right)^{\frac{\alpha\beta}{2}} = G_c(\bar{\gamma}) - G_d^{FSO}, \quad (8)$$

where $G_c = \left(\frac{\gamma_{th}}{(\eta I^a)^2} \right)^{\frac{\alpha\beta}{2}}$ defines the shift of the curve in SNR and $G_d^{FSO} = \frac{\alpha\beta}{2}$ presents the diversity order.

For the RF transmission, we need to apply Maclaurin series expansion [23] for the exponential function and consider only the first term as the higher-order terms are neglected. Accordingly, the OP at high SNR can be obtained as

$$P_{out,2}^\infty \simeq \mu \gamma_{th} \frac{1}{P_2 h_l / N_0}. \quad (9)$$

Thus, the diversity order is $G_d^{RF} = 1$ as we use a single antenna. Therefore, for State-0, where SC is adopted on the GS, the diversity gain is $G_d = \max(\frac{\alpha\beta}{2}, 1)$.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we evaluate the performance of our system in terms of outage probability. The satellite is assumed to be orbiting at an altitude of 500 km, communicating with a GS located at 0.8 km above sea level. For the FSO link, $\lambda = 1550$ nm wavelength is considered, whereas the RF link is operating at $f = 40$ GHz. For FSO communication, the zenith angle is set to $\xi = 65^\circ$, the nominal value of the refractive index is $C_0 = 5 \times 10^{-14}$ [9], and the wind speed is set to $v_g = 2.8$ m/s for thin clouds condition. In the presence of heavy rain, we consider $C_0 = 0.4 \times 10^{-14}$ [9], $v_g = 11.176$ m/s, and the specific attenuation of foggy weather is considered as 339.62 dB/km. For the RF link, we consider the presence of frequent heavy shadowing where $m = 1.0$, $b = 0.063$, $\Omega = 8.94 \times 10^{-4}$. Moreover, the transmitter and receiver gains are set to $G_T = G_R = 45$ dB, the oxygen scattering parameter $\omega_{oxy} = 0.1$ dB/km, and the rain rate is given as $\mathcal{R} = 25$ mm/h. Furthermore, in the presence of non-zero boresight pointing errors, we set $\theta = 0.2$ mrad, $\sigma_s = 20$ cm and we consider different sizes of boresight and aperture. In all simulations, the threshold is set to $\gamma_{th} = 7$ dB. Without loss of generality, we simply assume that the different states of weather have the same probability of occurrence satisfying $\sum_{k=0}^2 p_k = 1$. Thereafter, the probabilities

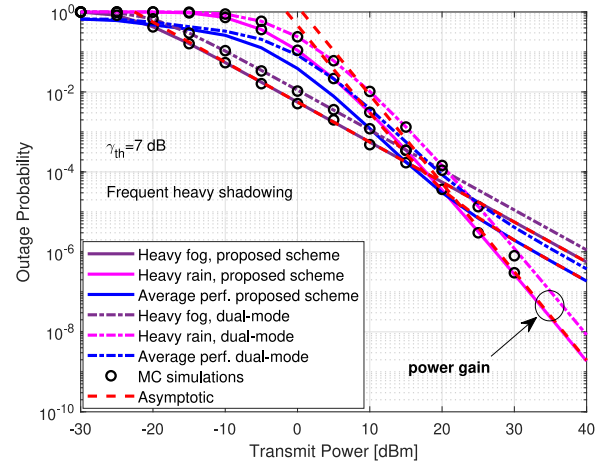


Fig. 2. Outage probability performance of the proposed scheme.

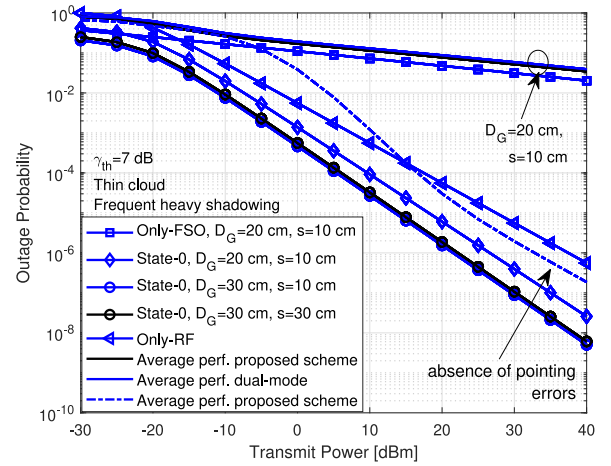


Fig. 3. Outage probability performance of the proposed scheme in the presence of non-zero boresight pointing errors.

are given as $p_k = 1/3$ for $k = 0, 1, 2$. In addition, we compare our proposed scheme with the conventional dual-mode hybrid RF/FSO, in which the total power is always divided into $P_t/2$ for all states. Finally, the derived expressions are verified using Monte Carlo (MC) simulations, however, not explicitly included to guarantee the clarity of the figure.

Fig. 2 illustrates the outage probability vs. transmit power for the proposed strategy in the absence of pointing errors. As we can see, the analytical results match the MC simulations with good accuracy. In addition, the high SNR analysis shows that for the heavy fog state, the overall gain is 1, whereas, for the heavy rain state, the overall gain is close to $\frac{\alpha\beta}{2} = 2.2117$. Moreover, as can be seen in the figure, at lower transmit power, the performance of foggy weather is better than the performance of rainy weather. However, after $P_t = 16$ dBm, the performance of rainy weather improves, causing a crossing point between the two curves. We also compare our proposed strategy with the dual-mode scheme. Furthermore, the figure shows that the proposed strategy achieves better outage performance than the conventional dual-mode hybrid RF/FSO communication.

Fig. 3 investigates the impact of non-zero boresight pointing errors and the impact of aperture averaging for the proposed scheme. It is clear from the figure, that the average performance of the proposed scheme highly deteriorates in the

presence of boresight non-zero pointing errors. As observed in the figure, for thin cloud conditions, the proposed hybrid RF/FSO configuration performs better than FSO-only and RF-only transmissions. In addition, in the presence of non-zero boresight pointing errors, we can observe that the proposed strategy performs better than the dual-mode hybrid communication. Moreover, we can see that the RF-only scheme outperforms the FSO-only scheme due to the huge impact of non-zero boresight pointing errors. Furthermore, the results demonstrate that increasing the aperture size D_G enhances the overall performance by reducing the impact of atmospheric turbulence and pointing errors. Also, when the boresight displacement s increases, the misalignment between the satellite and the GS increases, therefore, less power is collected by the receiver aperture yielding a serious degradation in the OP performance.

In summary, we provide some important design guidelines that can be helpful for the design downlink hybrid RF/FSO SatCom systems.

- We observe from the results that the proposed model is superior to the dual-mode hybrid RF/FSO communication method for SatCom.
- In the absence of pointing errors, only at lower transmission power, the RF communication outperforms FSO communication. However, in the presence of non-zero boresight pointing errors, the RF transmission performs better than FSO transmission.
- The results have shown that the non-zero boresight pointing errors strongly deteriorates the overall performance of FSO communication as it increases the misalignment between communicating parts.
- It is shown in Fig. 3 that the aperture averaging technique is an effective solution in SatCom to mitigate the effects of atmospheric turbulence and pointing errors.

V. CONCLUSION

In this letter, we have proposed a new soft-switching setup for hybrid RF/FSO downlink SatCom. According to the context-aware by the measurements of sensors system, an LEO satellite adapts its power and switches between RF and FSO links by selecting the channel with the highest performance based on the weather conditions. To quantify the performance of our model, outage probability expressions are derived and simulation results are provided to confirm the accuracy of our analytical results. Moreover, the results have shown that our proposed strategy improves power efficiency compared to the conventional dual-mode hybrid RF/FSO. Furthermore, we have studied the impact of non-zero boresight pointing errors to observe the misalignment effect for hybrid RF/FSO communication. The study indicates that increasing the boresight leads to severe performance degradation. However, the aperture averaging technique can be used to improve the performance and alleviate pointing errors effects. Finally, some significant design guidelines are suggested.

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