Coherent vs IM/DD Transmissions for FSO Communications in the Presence of Atmospheric Turbulence

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***Abstract*—We investigate the performance of free-space optical communication systems in the presence of atmospheric turbulence with the purpose of assessing the advantages that a coherent communication system can bring with respect to a conventional intensity modulation/direct detection system. The perspective is an information theoretic one, hence we evaluate the mutual information and the corresponding outage probability of both channels, with traditional symbol constellations, as a pragmatic approximation to the capacity, or to the outage capacity, of those channels. In addition, we analyze non-uniform symbol constellations, in order to evaluate the possible shaping gain that can be achieved under different channel conditions.**

I. Introduction

Free-space optical (FSO) systems, like early fiber optic communication systems, have traditionally resorted to intensity modulation and direct detection (IM/DD) techniques, both for indoor communications [1] and for low Earth orbit (LEO) satellite to ground links [2], [3].

We focus on the latter scenario for which the presence of atmospheric turbulence is considered to be the principal impairment. Turbulence has an attenuating effect on the received power, known as *optical scintillation*, that can be modeled by a log-normal (LN) or by a gamma-gamma distribution [4]. Given the long coherence time of scintillation compared to the duration of transmitted codewords, typically in the order of milliseconds, a block-fading model is appropriate for the FSO channel, unless a long interleaver is adopted, which is often considered to be impractical [5]. As a consequence, under the block-fading hypothesis, *outage probability* should be considered as the appropriate metrics to characterize the channel.

For IM/DD optical transmission systems, the symbol constellation belongs to $\mathbb{R}^+$, i.e., only real and positive light intensities are allowed. The channel capacity of such a FSO intensity modulated system has been studied in the literature. In [5], the capacity-achieving non-uniform input signal distribution is evaluated considering constraints on the average intensity as well as on the peak optical power, showing that substantial performance improvements can be achieved by a proper shaping of the symbol constellation.

The adoption of coherent transceivers for FSO communications opens up the field of investigation to similar analyses, performed on a different channel model, where a general complex optical field, i.e., belonging to $\mathbb{C}$ and with signed components, carries the information [6], enlarging the signal space by a factor 2. A further doubling of the signal space is provided by the possibility to exploit polarization division multiplexing, with coherent transceivers, thus yielding a factor 4 for the overall enlargement of the signal space. Albeit, for the sake of simplicity, we shall restrict our attention on the in-phase (i.e., real) component of the complex optical field envelope, keeping in mind a potential increase by a factor of 4 in the achievable rates.

In this work, we explore a comparison between IM/DD solutions and a coherent transceiver for FSO transmissions in a LEO satellite-to-ground link, by means of mutual information and related system outage probabilities, for practical signal constellations. In order to keep the analysis at an affordable level, we refer to simple cases where the transmission channel can be modelled as an additive Gaussian channel with fading due to optical scintillation. Thus, we neglect the effects of optical shot noise and the presence of signal-noise beat terms, especially in coherent receivers.

Different receivers employing different technological solutions imply different noise figures, besides different costs, that cannot be directly compared. Given that in satellite transmissions, the average transmitted power is the main scarce resource, we shall adopt it as the main term of comparison, for the two kinds of systems, leaving the additive noise level as an extra variable that should be separately evaluated on a techno-economical basis, although we shall provide some values of practical interest. The effect of optical scintillation shall be modeled as a LN variable, which is considered to be accurate in the present case of moderate atmospheric turbulence (whereas the gamma-gamma distribution is preferred when large scintillation indices, i.e., above 1, are at hand [4]).

II. System model

In order to compare FSO transmission systems of different nature, such as those employing a coherent or an IM/DD transceiver, different system models are analyzed so as to evaluate their respective channel capacity and the achievable mutual information for given input signal statistics that obey some prescribed constraints. In both cases, the physical channel, i.e., the transmission medium, is the same and is assumed to suffer only from the atmospheric turbulence effect, which introduces a random fading that is not frequency selective across the transmission bandwidth. The only other impairment is additive white Gaussian noise (AWGN) that may be due to different physical sources, such as an amplified spontaneous emission (ASE) noise source introduced at the optical amplification stage in the front-end of a coherent receiver, or due to thermal noise introduced at the transimpedance amplifier (TIA) stage that follows the avalanche photodiode (APD)

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for the intensity detection of modulated light, plus possible ambient light induced shot noise.

A. Intensity Modulation and Direct Detection System

The optical transmission system architecture that is expected to require less resources and, therefore, to exhibit a worse performance is the traditional solution based on intensity modulation at the transmitter side and direct detection of the received light power at the receiver side. Despite this is the oldest solution adopted in optical communications, it is still widespread nowadays when short-reach links and cost constraints make it preferable, compared to more costly and performing solutions. Despite FSO satellite-to-ground links have little to share with short-reach terrestrial links, the long-lasting history of IM/DD systems turns out to be a positive factor in terms of robustness and reliability in space applications.

The receiver that we shall investigate in the present case is a very simple and traditional one, made of an APD at the front-end for opto-electronic conversion, followed by a TIA, that introduces extra thermal noise. We shall assume, however, that the APD excess noise factor is small enough to make shot noise negligible, compared to thermal noise, so that the TIA is the dominant source of noise and thus a traditional AWGN model applies to the system, as in [5], where the additive Gaussian noise is independent of the received signal. In the absence of intersymbol interference, the very simple discrete-time channel model that characterizes the IM/DD system is thus

$$Y = \alpha H P X + W \,, \tag{1}$$

where $P > 0$ is the parameter that drives the transmitted optical power and $X \in \mathbb{R}^+$ is the transmitted symbol, belonging to a given constellation, whereas $H \sim p_H(h)$ is the random fading of the light intensity that is due to atmospheric turbulence and that is known as optical scintillation. The parameter α, instead, represents the power attenuation due to path loss and to any other constant loss factor that can be computed from the link budget, as detailed in Sec. III-C. Hence, the received light intensity in the absence of fading and noise is $\alpha P X$, which is in turn equal to the photodetected current.[1] In (1), $W \sim \mathcal{N}(0, \sigma_W^2)$ is the zero-mean real AWGN that stems from thermal noise samples, as generated by the receiver TIA, whose variance is known to be

$$\sigma_W^2 = \frac{4kT_0}{R_L}\Delta f \,, \tag{2}$$

being k is the Boltzmann's constant, T_0 the receiver temperature and R_L the load resistance of the photodetector plus that of the TIA.

The output signal $Y \in \mathbb{R}$ in (1) is thus real and the electrical signal-to-noise ratio (SNR), for a realization h of the scintillation is

$$\mathsf{SNR}_{\mathsf{IM/DD}}(h) = \alpha^2 h^2 \frac{P^2 E\left[X^2\right]}{\sigma_W^2} = \alpha^2 h^2 \frac{(PE\left[X\right])^2 K^2}{\sigma_W^2} \,, \tag{3}$$

where $(PE\left[X\right])$ is the average transmitted optical power and

$$K = \frac{\sqrt{E\left[X^2\right]}}{E\left[X\right]} \tag{4}$$

defines a constellation-dependent factor that is equal to the ratio between the root mean square and the average symbol value.

The presence of P^2 in (3) should not surprise since P is related to the optical power, which is proportional to the photodetected electric current, whose power is in turn proportional to the *electrical SNR*. In fact, it is the electrical SNR in (3) that dictates system performance and that is the main figure on which the bit error rate (BER), as well as the mutual information, can be evaluated.

B. Coherent Transmission System

For a coherent FSO transmission system, it is the complex optical field envelope $X \in \mathbb{C}$ that is detected by the so-called $90°$-*hybrid* optical circuit, that is at the core of a coherent transceiver [7]. The two couples of *balanced photoreceivers* that follow the hybrid allow the detection of the in-phase and quadrature components of X as it usually occurs in radiofrequency communications. The beating of the signal with a local oscillator[2] yields the real and imaginary parts of the complex envelope X of the light field, so that two-dimensional modulation schemes, such as QAM or PSK (for uniformly distributed signals), are affordable. Typically, the polarization of light is exploited as a further dimension to multiplex signals with orthogonal states of polarization, thus increasing the information bearing capacity of the FSO channel by a factor 2, but, as already stated in Sec. I, in the analytical expressions that follow, we will consider only the in-phase component of a single polarized signal.

The discrete-time channel model, after analog-to-digital (A/D) conversion, is

$$Y = \sqrt{\alpha}\sqrt{H}\sqrt{P}X + W \,, \tag{5}$$

where, similarly to (1), the parameter $P > 0$ drives the transmitted optical power and $X \in \mathbb{C}$ is the complex transmitted symbol, belonging to a two-dimensional constellation, so that $\sqrt{P}X$ is the complex envelope of the transmitted optical field. Being H the optical scintillation, i.e., the random power attenuation affecting the optical intensity, the random amplitude attenuation is its square root, as appears in (5). Similarly, $\sqrt{\alpha}$ includes the constant amplitude attenuation factors coming from the link budget (see Sec. III-C). Finally, $W \sim \mathcal{CN}(0, \sigma_W^2)$ is the complex normal zero-mean AWGN with variance $\sigma_W^2/2$ per component that affects the received signal samples.

The average transmitted optical power, for the coherent channel model, is $PE\left[|X|^2\right]$, so that the SNR obtained from

[1] We assume, without loss of generality, that the responsivity of the photodiode providing the opto-electronic conversion is 1 [A/W].

[2] Although the local oscillator might not be perfectly tuned to the optical carrier frequency and might not at all be locked to the carrier phase, we can conceptually refer to the coherent receiver as a classic homodyne receiver scheme.

(5), for a given value $H = h$ of the scintillation, is

$$\mathsf{SNR}_{\mathsf{coh}}(h) = \alpha h \frac{PE\left[|X|^2\right]}{\sigma_W^2} \tag{6}$$

resulting in an expression that significantly differs from the corresponding one for the IM/DD case in (3).

Different receiver architectures could be envisaged to implement a coherent transmission link. However, since the coherent format is not a consolidated choice but rather a novel solution to be tested in FSO systems, we refer to the architecture that is most commonly adopted in coherent fiber-optic links, consisting in the cascade of an optical amplifier followed by the proper coherent receiver, made of a 90°-hybrid and of the balanced photodetectors that follow [7]. The optical amplifier, usually with a large gain, brings the (weak) received optical signal to a sufficient optical power level that allows an effective opto-electronic (O/E) conversion, at the coherent receiver front-end, that is not impaired by severe shot noise. Within this scenario, it is reasonable to assume that the dominant source of noise is the ASE that spontaneously arises in the preamplifier and that adds to the useful signal before the O/E conversion. The (white) power spectral density of ASE noise, at the amplfier output, is evaluated after a quantum description of the spontaneous emission process occurring in multiband excited ions (e.g., of Erbium), and is known to be

$$S_{ASE} = 2n_{sp}h\nu_0(G-1)\,, \tag{7}$$

where n_{sp} is the *spontaneous emission factor*, also known as *population inversion factor*, with typical values $1.5\div 2$, and the factor 2 accounts for the two optical polarizations with which a photon can be spontaneously emitted. By integrating S_{ASE} over the signal bandwidth Δf, the total ASE noise variance turns out to be

$$\sigma_{ASE}^2 = 2n_{sp}h\nu_0(G-1)\Delta f\,. \tag{8}$$

If we assume that the ASE component orthogonal to the signal polarization is filtered out, then only the noise component that is co-polarized with the signal must be accounted for, and (8) is divided by 2. Considering ASE noise at the amplifier input, its variance in (6) is thus $\sigma_W^2 = \sigma_{ASE}^2/(2G) = n_{sp}h\nu_0(1-1/G)\Delta f$. Besides representing a traditional solution in fiber optic systems, the optically preamplified coherent receiver thus justifies the additive Gaussian channel model in (5).

C. Statistics of scintillation

We assume a LN distribution for the scintillation H, i.e., $H \sim \mathcal{LN}(\mu_N, \sigma_N^2)$, so that its probability density function (pdf) is

$$p_H(h) = \frac{1}{h\sqrt{2\pi\sigma_N^2}} \exp\left\{-\frac{(\ln(h)-\mu_N)^2}{2\sigma_N^2}\right\}\,, \tag{9}$$

with mean and variance given by the following expressions

$$\mu_H = \exp\left\{\mu_N + \sigma_N^2/2\right\} \tag{10}$$

$$\sigma_H^2 = \exp\left\{2\mu_N + \sigma_N^2\right\}\left(\exp\left\{\sigma_N^2\right\} - 1\right)\,. \tag{11}$$

The strength of the optical scintillation phenomenon is usually characterized by the power scintillation index (PSI), defined as the normalized variance of the received intensity, whose expression is thus

$$S \triangleq \frac{E\left[H^2\right]}{E\left[H\right]^2} - 1 = \frac{\sigma_H^2}{\mu_H^2} = \exp\left\{\sigma_N^2\right\} - 1 \tag{12}$$

which depends uniquely on σ_N^2 and not on μ_N.

A LN distribution for the scintillation parameter H is considered accurate at low to moderate scintillation indices values, e.g., when S is in the order of 0.1, a value corresponding to a $10°$ elevation for a satellite transmitting at 847 nm lightwave carrier, or to a $18°$ elevation for a satellite transmitting in the 'third window' (1550 nm) [6]. When more severe atmospheric conditions imply larger values of S, e.g., in the order of 1.0, then other distributions like the Gamma-Gamma or the K-distributions are considered more accurate [4].

The pdf in (9) has the nice feature that any power of H, including its square root or its inverse, is LN too. This is clearly a consequence of the well known property that a linear transformation of a normal variable is again normal (with proper shifting of the mean and scaling of the variance). Since, by the definition of a LN variable H it holds $N = \ln H \sim \mathcal{N}(\mu_N, \sigma_N^2)$, a linear transformation $N \to aN + b$ results in a corresponding transformation $H \to \exp(aN+b) = \mathrm{e}^b H^a$, i.e., in a multiplication and a power transformation of the original LN variable. As a result, $\sqrt{H}$ in (5) has a pdf similar to H in (1), except for a modification of its mean and variance.

III. Channel Capacity and Information Rate

The evaluation of channel capacity for the IM/DD system described by (1), subject to an average power constraint, depends on the presence of a sufficiently long interleaver, that is able to average out the impact of the quasi static fading due to scintillation. If this is the case, one can compute classical *Shannon capacity* C, where

$$C = \int C(h)p_H(h)dh \tag{13}$$

is found by averaging the channel capacity $C(h)$ conditioned on a given value for the scintillation $H = h$. Since (1) and (5) represent additive Gaussian channels, if we consider the constraint on average power only, then we can recover the celebrated result by Claude Shannon,

$$C(h) = B\log\left(1 + SNR(h)\right) \tag{14}$$

where B is the channel bandwidth, as measured in bits per second. In (14), the SNR is evaluated for a given value of the scintillation, hence it corresponds to either (3) or (6), for the two system models considered here, while the effective received SNR is its average, e.g., for a coherent system, $SNR = E\left[SNR(H)\right] = \mu_H \alpha PE\left[|X|^2\right]/\sigma_W^2$.

A similar calculation can be carried out for the mutual information (MI)

$$I(X;Y) = \int I(X;Y \mid H=h)p_H(h)dh \tag{15}$$

by averaging on the conditional mutual information that can be achieved with a given scintillation value $H = h$, by using standard modulation formats (BPSK, QPSK, M-PSK, 16-QAM, etc). As it is known, the envelope of these curves of mutual information, using signal constellations with increasing cardinality, yields a lower approximation to the actual capacity (13).

If instead the use of a very long interleaver is unfeasible, a block fading channel model is considered to analyze the performance of the FSO links, as in [5]. In these channels, the modulated codeword is partitioned into L blocks, where L is called diversity order of the system. They rely on the assumption that the channel gain H_i is constant over one block of transmission, and independent and identically distributed (i.i.d.) over different blocks. Due to the limited number of realizations of the channel gain, the impact of very low channel gain values cannot be averaged out, which in our case yields a null *Shannon capacity*. Hence, the outage capacity is the proper metrics for system performance, whose expression is given below for the two kinds of systems.

In both systems of interest we assume, without loss of generality, that H is normalized so that its mean value $\mu_H = 1$, i.e., that $\mu_N = -\frac{\sigma_N^2}{2}$ in (10). In the following, we select $\sigma_N^2 = 0.1$, which can be converted to the power scintillation index S as in (12). This value is typical for atmospheric channels with moderate turbulence, as stated in Sec. II-C.

A. Intensity Modulation and Direct Detection System

For an IM/DD system, we modulate the transmitted signal by the on-off keying (OOK) modulation. By resorting to the discrete-time channel model in (1), αHPX is the noiseless received light intensity in the presence of fading.

We impose a normalization of the symbol constellation,

$$E[X] = 1, \qquad (16)$$

so that the average transmitted optical power $(PE[X])$ in (3) is P. As a consequence, for a given realization of the scintillation $H = h$, the instantaneous SNR in (3) becomes

$$\mathsf{SNR}_{\mathsf{IM/DD}}(h) = \alpha^2 h^2 \frac{P^2 K^2}{\sigma_W^2} = \alpha^2 h^2 \frac{E_s}{N_0}\,, \qquad (17)$$

where E_s/N_0 is the transmitted energy per symbol divided by the noise power spectral density.

For an ergodic fading channel the capacity $\mathsf{C}_{\mathsf{IM/DD}}$ is

$$\mathsf{C}_{\mathsf{IM/DD}} = \max_{P(x)} \int_0^\infty \mathsf{I}(X;Y|H=h)\, p_H(h)\, \mathrm{d}h \qquad (18)$$

where the MI $\mathsf{I}(X;Y|H=h)$ in (18) corresponds to the MI of an AWGN channel with instantaneous $\mathsf{SNR}_{\mathsf{IM/DD}}(h)$.

For the block fading channels, we define first the outage probability as the probability that the transmission rate R exceeds the average instantaneous MI over L blocks, i.e.,

$$p_{\mathsf{out,IM/DD}}(\mathsf{R}) = \Pr\left\{\max_{P(x)} \frac{1}{L}\sum_{\ell=1}^{L} I(X,Y,H_\ell) < \mathsf{R}\right\} \qquad (19)$$

where the random variable (r.v.) $I(X,Y,H_\ell)$ is the rate supported in block ℓ with values $\mathsf{I}(X;Y|H_\ell = h)$. The $\epsilon-$outage capacity is the maximum transmission rate such that the outage probability is smaller than a target value ϵ,

$$\mathsf{C}_{\epsilon,\mathsf{IM/DD}} = \operatorname*{argmax}_{\mathsf{R}} p_{\mathsf{out,IM/DD}}(\mathsf{R}) < \epsilon. \qquad (20)$$

The resulting average communication rate is

$$\bar{\mathsf{R}}_{\epsilon,\mathsf{IM/DD}} = (1-\epsilon)\mathsf{C}_{\epsilon,\mathsf{IM/DD}}. \qquad (21)$$

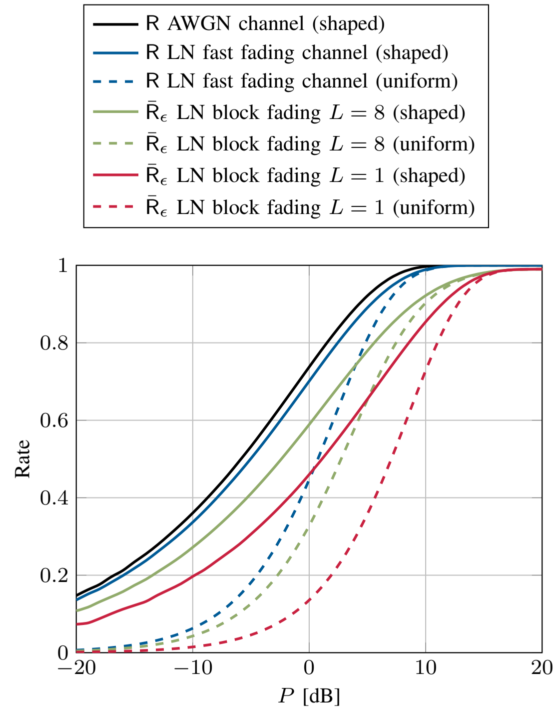

Figure 1. Average rate in (21) for an IM/DD system: OOK transmission over AWGN, fast fading, and block fading channels; see text for parameters' values.

It is worth noting that in the SNR expressions (3) and (17), the square of the scintillation realization h^2 appears for the IM/DD case, whereas h appears for the coherent case (6). As discussed in Sec. II-C, any power of H is still LN distributed, so that, by applying the quadratic transformation to H, it is easy to show that $H^2 \sim \mathcal{LN}(2\mu_N, 4\sigma_N^2)$.

Average rates $\bar{\mathsf{R}}_{\epsilon,\mathsf{IM/DD}}$ versus the average transmitted optical power P for uniform and shaped OOK constellations are depicted in Fig. 1, assuming $\sigma_W^2 = 1$ and $\alpha = 1$, for the AWGN channel, the fast fading channel, and the block fading channel with $\epsilon = 10^{-2}$. Note that, by applying shaping, we get an increasing gain for decreasing P.

B. Coherent Transmission System

For ease of presentation, we consider one dimension of the signal for analysis, i.e., the in-phase (or, alternatively, the quadrature) component, hence only the corresponding noise component, with power $\sigma_W^2/2$, is accounted for. In the discrete-time system model in (5), the modulation symbol X is thus an M-ary amplitude shift keying (ASK) symbol (rather than a complex quadrature amplitude modulation (QAM)

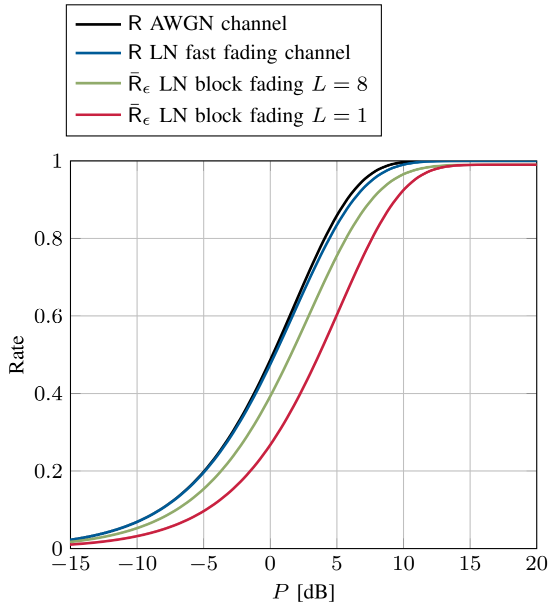

Figure 2. Average rate in (27) for a coherent system: 2-ASK transmission over AWGN, fast fading, and block fading channels; see text for parameters' values.

symbol). In a coherent transmission system, we impose a different normalization of the symbol constellation,

$$E\left[|X|^2\right] = 1\,, \tag{22}$$

so that the average transmitted optical power is $PE\left[|X|^2\right] = P$. As a consequence, for a given scintillation value $H = h$, the instantaneous SNR in (6) reduces to

$$\mathsf{SNR}_{\mathsf{coh}}(h) = \alpha h \frac{P}{\sigma_W^2/2} = \alpha h \frac{E_s}{N_0}\,, \tag{23}$$

where E_s/N_0 has the same meaning as in (17).

For an ergodic fading channel the capacity is

$$\mathsf{C}_{\mathsf{coh}} = \max_{P(x)} \int_0^\infty \mathsf{I}\,(X;Y|H=h)\, p_h(h)\, \mathrm{d}h \tag{24}$$

where the MI $\mathsf{I}\,(X;Y|H=h)$ in (24) corresponds to the MI of an AWGN channel with instantaneous $\mathsf{SNR}_{\mathsf{coh}}(h)$.

For the block fading channels, similarly to the IM/DD case, the outage probability is

$$p_{\mathsf{out,coh}}(\mathsf{R}) = \Pr\left\{\max_{P(x)} \frac{1}{L}\sum_{\ell=1}^{L} I(X,Y,H_\ell) < \mathsf{R}\right\} \tag{25}$$

where the r.v. $I(X,Y,H_\ell)$ denotes the rate supported in block ℓ with values $\mathsf{I}(X;Y|H_\ell = h)$. The ϵ-outage capacity $\mathsf{C}_{\epsilon,\mathsf{coh}}$ for the block fading channel is then

$$\mathsf{C}_{\epsilon,\mathsf{coh}} = \operatorname*{argmax}_{\mathsf{R}}\, p_{\mathsf{out,coh}}(\mathsf{R}) < \epsilon. \tag{26}$$

In average, error-free communications is possible with rate

$$\bar{\mathsf{R}}_{\epsilon,\mathsf{coh}} = (1-\epsilon)\mathsf{C}_{\epsilon,\mathsf{coh}}. \tag{27}$$

Fig. 2 shows the average rates $\bar{\mathsf{R}}_{\epsilon,\mathsf{coh}}$ versus the average transmitted optical power P, assuming $\sigma_W^2/2 = 1$ and $\alpha = 1$, for uniform (capacity-achieving distribution) 2-ASK, obtained in the case of an AWGN channel, a fast fading channel, and a block fading channel with $\epsilon = 10^{-2}$.

Table I
RECEIVER PARAMETERS AND RESULTING NOISE VARIANCE, FOR IM/DD AND PREAMPLIFIED COHERENT RECEIVERS.

Parameter	Value
Total optical power loss α^{-1}	51.8 dB
Responsivity R_d	1.0 A/W
Load+Feedback resistance R_L	160 Ω
Load+Feedback capacitance C_L	0.2 pF
Temperature T_0	290 K
Thermal Noise variance σ_W^2	-123.0 dB
receiver bandwidth Δf	5 GHz
Amplifier Gain G	23 dB
Carrier wavelength λ_0	1550 nm
Spontaneous emission factor n_{sp}	1.75
ASE Noise variance $\sigma_{ASE}^2/(2G)$	-89.5 dB

C. Comparison of IM/DD and Coherent Systems

It is evident that the two kinds of system described in Sec. II-A and Sec. II-B are totally different, both in the transmission strategy and in the receiver architecture. Albeit, both have been modelled, under proper technological constraints, by a classical *additive Gaussian memoryless channel*, that is relatively easy to analyze.

Despite the transmission medium is the same, for the two kinds of system, the transceivers are different and are affected by physically different sources of noise, for which a direct comparison is not feasible. However, the two kinds of transmitters both rely on the average optical power, which is the main scarce resource, on board the satellite, hence it is absolutely meaningful to directly compare different solutions to exploit a given average power at the transmitter, whose limit shall eventually be dictated by the solar cells, batteries and all power-supply devices on board. Hence, we wish to adopt a more general perspective to compare the performance of an IM/DD and a coherent system, that is based here on the average transmitted optical power, which appears in both Fig. 1 and Fig. 2 that report the information rates and that describe system performance.

For the purpose of directly comparing the performance that is achievable by the two types of systems, receiver noise and channel attenuation should then be evaluated and accounted for. Fortunately, this is feasible in an a-posteriori way, thanks to the fact that the systems are modelled as additive Gaussian channels, in (1) and (5).

In order to compute the link budget that determines the optical power loss α^{-1}, we resort to the channel parameters reported in Table III in [2], which considers different sectors, i.e., different angular ranges, under which the ground station sees the satellite. Assuming the most favorable FSO channel characteristics, with an elevation angle between 37 and 90 degrees, corresponding to 'sector 6' in [2], the link budget yields a total optical power loss amounting to $\alpha^{-1} = 51.8$ (dB). Table I reports this figure, along with some typical values for the receiver parameters of an IM/DD receiver, still consistent with [2], or of a preamplified coherent receiver. We assume a symbol rate equal to 10 GBd, hence the (one-sided) bandwidth of the receiver is set equal to half the symbol rate, i.e., $\Delta f = 5$ GHz, as also results in the IM/DD case where, by a simple single-pole approximation, it is $(2\pi R_L C_L)^{-1} \simeq 5$ GHz. This, in turn, yields the variance of the thermal noise (2) and of the (single-polarization) input ASE noise, whose values are reported in Table I. While channel attenuation is common to both kinds of system, the impact of noise is very different due to the profound technological differences.

Results in Secs. III-A and III-B were plotted versus normalized abscissas. Recall that the variance of the additive Gaussian noise was normalized to $\sigma_W^2 = 1$ in the IM/DD case, and to $\sigma_W^2/2 = 1$ in the coherent case. The sources of non-random attenuation are neglected, i.e., we assumed $\alpha = 1$. In order to account for these effects when comparing corresponding curves in Figs. 1 and 2, the curve from the IM/DD system must be shifted to the right by $10\log_{10}(\sigma_W/\alpha)$ and that of the coherent system must be shifted to the right by $10\log_{10}(\sigma_W^2/(2\alpha))$. We exemplify this in Fig. 3, that shows the comparison between the two systems by considering, for example, transmission over the AWGN channel, with OOK and 2-ASK modulations in the case of the IM/DD and coherent systems, respectively. Therein, the curve in Fig. 1 is shifted to the left by $10\log_{10}(\alpha/\sigma_W) = 9.7$ dB, where we used the values in Table I for the total optical power loss and the thermal noise variance, while that of the coherent system in Fig. 2 is shifted to the left by $10\log_{10}(2\alpha/\sigma_W^2) = 40.7$ dB, where the values of α and that of the ASE noise variance $\sigma_W^2 = \sigma_{ASE}^2/(2G)$ are again taken from Table I. This changes completely the trend that appears from the Figures in Secs. III-A and III-B. Note that the presence of a square power on the coherent case only is not a contradiction but, rather, is the very consequence of the different system models in (1) and (5), where the different technological solutions imply different costs, that are not accounted for in the comparison.

IV. Conclusions

We evaluated the information rates of two FSO communication systems impaired by atmospheric turbulence, for both ergodic fading and block fading channels. In the presence of the same transmission medium, the two systems adopt a coherent or a more traditional IM/DD transceiver, respectively. The average transmitted optical power was considered to be the main resource, especially in a LEO satellite downlink, that we considered for comparing the two systems.

Relying on simple but meaningful channel models, we highlighted how the physical channel parameters (i.e., the optical power loss and the random fading due to turbulence) as well as the transceiver parameters (i.e., the transmitted optical power, the symbol constellation and the receiver noise) affect the two types of systems in different ways. In particular, the profound technological difference of the two solutions implies that receiver noise stems from physically different sources and reaches very different levels, for typical system parameters,

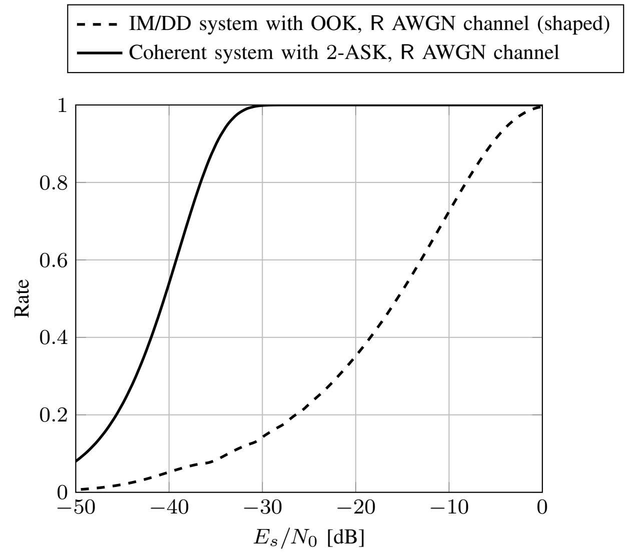

Figure 3. Comparison of IM/DD and coherent systems, transmitting binary symbols over the AWGN channel.

giving a clear advantage to the more costly and performing coherent system, even when polarization multiplexing is not exploited.

While the comparison of an IM/DD and a coherent lightwave system may sound unfair and its outcome may appear rather obvious, however, the value of the method that we proposed lies in the possibility to exactly quantify the gain that the coherent solution can achieve, in terms of signal to noise ratio, and compare it against the higher cost that it implies. The comparison should thus be performed on a techno-economical basis, that goes beyond the scope of this work.

Another result that we found is that a significant shaping gain can be achieved for OOK modulation in an IM/DD system. In addition, for the block-fading channel model, we also quantified the gain in performance that can be achieved through an increased diversity order.

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