Experimental Study of the Impact of Molecular Absorption on Coherent Free Space Optical Links

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Abstract *We study the impact of molecular absorption on free space coherent communication signals with an optical set up incorporating a gas cell. We show that worst-case absorption at 1.5-1.6 µm can be mitigated with constant modulus equalization and <1 dB additional signal launched power.*

Introduction

Users living in areas with low density population, in landlocked countries or recovering from a disaster would enjoy a better quality of life with greater access to communications by satellite. Today's satellites largely use radio technologies where spectral resources are scarce. By contrast, free space optics can provide a larger (unlicensed) bandwidth while reducing the equipment size, weight and power consumption by >50%[1,2]. While state of the art free space optical links carries 10 Gbps data[3], digital coherent optics could bring a capacity leap with ≥100 Gbps per optical link. However, free space optical links suffer from several specific impairments[1]. For instance, the atmosphere may severely impact the optical beam because of absorption by gases. In the L band particularly[4,5], carbon dioxide has ~90 absorption lines between 186-192 THz. The absorption linewidths and depths can go up to several GHz and tens of dB, respectively, depending on the propagation distance. The risk of a harmful performance penalty when signal frequencies overlap one or several lines, suggests avoiding spectral windows where absorption is strong, e.g. in the L-band, which limits the achievable system capacity. While this effect has been studied numerically for direct detection[5], we consider in this paper signals detected by a coherent receiver equipped with digital equalization[6].

In this work, we evaluate experimentally the effect of molecular absorption on 100 Gbps (net) signals. Firstly, we describe the set up emulating free space absorption with a gas cell. Secondly, we discuss the behavior of the constant modulus equalizer to recover molecular absorption impairments. Finally, we discuss how this can be used to tune design parameters such as the symbol rate and the optical launched power.

System description

The fibered set up is shown in Fig. 1a. We use a 5 cm-long gas cell filled with acetylene (C_2H_2) at the pressure of 50 Torr as absorption medium[7]. With respect to CO_2, C_2H_2 is much more absorbent and we obtain over cm distances similar absorption lines as CO_2 over the entire atmosphere[4,5]. The light can travel one or two pass(es) through the cell, hence varying the absorption levels, or just travel in a reference path, used for measurements in the absence of molecular absorption or when absorption is emulated digitally. Even though we use C_2H_2 absorption lines in C-band, the effect of a given absorption line depends only on the linewidth and depth, regardless of the type of gas. Hence, the results apply to other absorptive gases, e.g. CO_2 in L-band or H_2O in C-band[4,5].

For conciseness, we consider the deepest absorption line of C_2H_2, located at ~195,895 GHz (~1530 nm)[7]. The measured intensity responses for single and dual passes are shown in Fig. 1b (up). They are obtained by engineering a square spectrum of width ~60 GHz with our digital transmitter and recording the output spectrum with a high-resolution (~20 MHz) optical spectrum analyzer. They are well fitted by a Lorentz function of full width at half-maximum ~1.7 and ~2.5 GHz and depth ~12 and 24 dB, respectively. The phase response of the deepest

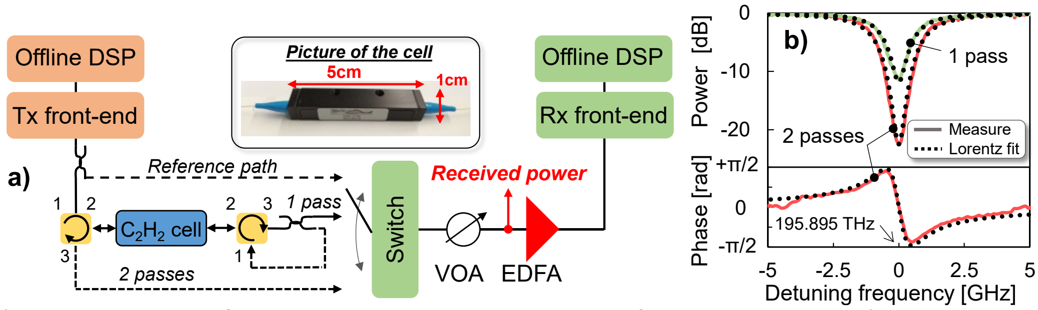

Fig. 1: a) Experimental set up. Open circles are optical circulators passing from 1 to 2 and 2 to 3. b) Up: intensity responses of the considered molecular absorption line. Bottom: phase response for two passes through the cell extracted from the equalizer response (full) and Lorentz model (dotted).

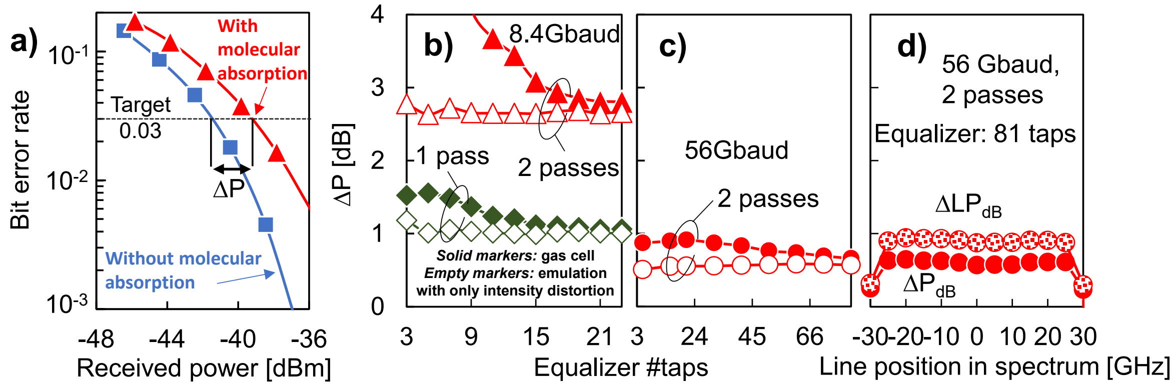

Fig. 2: a) Example of bit error rate versus received power curve. b) Received power penalty (ΔP_{dB}) at 5.3 dB signal-to-noise ratio for 8.4 Gbaud. c) ΔP_{dB} for 56 Gbaud. d) Effect of the absorption line position on signal spectrum on received power penalty ΔP_{dB} (solid circles) and additional required launched power ΔLP_{dB} (dotted circles) on 56 Gbaud.

absorption line is also shown in Fig. 1b (bottom). It is extracted from the phase transfer function of the equalizer used for demodulation (see next section) and is well fitted (dotted line) by modeling the permittivity with the Lorentz model[8,9].

Experiments and analysis

For communication experiments, we use a dual-polarization quaternary phase shift keying (QPSK) signal. The input waveforms are engineered offline with root-raised-cosine filtering (rolloff 0.1), loaded into the memory of a 100 GS/s 8-bit digital-to-analog converter and recurrently transmitted. Before the receiver amplifier (EDFA), a variable optical attenuator (VOA) is used to vary the received optical power, reproducing free-space losses. At the receiver, the photocurrents from the coherent mixer are sampled by a 200 GS/s real-time oscilloscope and processed offline by successively: resampling at 2 samples per symbol, equalizing with constant modulus algorithm[6,10], decimating to 1 sample per symbol, compensating carrier frequency and phase, deciding symbols and counting errors over ~10^6 symbols.

Molecular absorption primarily affects the signal by reducing the received optical power. We denote the attenuation coefficient by α (α < 1) which is equal to the integral in the signal band of the product of the normalized signal spectrum and the absorption line intensity profile. To counteract this effect, the launched power (and thus the received power) is first increased by the inverse of the attenuation (1/α). However, a further increase ΔP of the launched power is necessary to meet the target error performance, owing to absorption-induced inter-symbol interferences. Thus, the additional launched power ΔLP_{dB} with molecular absorption is (in dB):

$$\Delta LP_{dB} = -\alpha_{dB} + \Delta P_{dB} \quad (1)$$

With the above definition, ΔP_{dB} would be zero if the attenuation from the absorption lines was flat across the signal spectrum. Any penalty ΔP_{dB} stems from distortions induced by the frequency dependence of the attenuation across the signal spectrum, which cannot be fully mitigated by receiver digital processing.

We first measure the penalty ΔP_{dB} for QPSK signals at 56 Gbaud (the symbol rate required for 100 Gbps with an error correction overhead (OH) of 100%) and at 8.4 Gbaud. The second smaller symbol rate was chosen to ease the visualization of molecular absorption impairements. Fig. 2a shows how we derive ΔP_{dB} from the uncoded bit error rate versus received power curve. ΔP_{dB} is measured at a given signal-to-noise ratio, which corresponds to a target bit error rate before forward error correction. We perform a first assessment of the molecular absorption by passing signal light through the C_2H_2 gas-cell, then we emulate digitally the molecular absorption line but considering only the intensity response. To this end, we add a programmable reshaping mask in the frequency domain just after performing QPSK modulation. The resolution of the digital mask can be derived from the converter sampling frequency (100 GS/s) and its memory size (2^{18} samples) and amounts to ~380 kHz, small enough to emulate faithfully the molecular absorption lines of several GHz width. This protocol enables us to understand how the absorption intensity and phase responses contribute to the performance. Fig. 2b shows ΔP_{dB} for 8.4 Gbaud as a function of the number of taps of the constant modulus equalizer. For two passes through the cell, ΔP_{dB} decreases continuously from >4 dB to ~2.7 dB when the equalizer number of taps is increased from 3 to 23 and saturates above. This shows that the channel impulse response duration to compensate for is 23/2≈12 symbols at 8.4 Gbaud. However, with only intensity distortion, ΔP_{dB} is almost constant regardless of the equalizer number of taps. We deduce from these observations that the phase distortion penalty is not negligible but is well mitigated if the equalizer window duration (number of taps) is sufficient. For one pass through the cell, the penalty ΔP_{dB} is smaller (<1.5 dB), owing to the reduction in absorption. Also, the influence of the phase distortion is reduced (<0.5 dB). When operating at the larger rate of 56 Gbaud (Fig. 2c), where the absorption line overlaps on a relatively smaller fraction of the signal spectrum, ΔP_{dB} is found reduced with respect to 8.4 Gbaud and does not exceed 1 dB for two passes though the cell. At this rate, the phase impulse response spreads overs more symbols than at 8.4 Gbaud and its mitigation requires a greater number of equalizer taps, as shown in Fig. 2c. However, significantly increasing this number (>50) brings only limited benefits because the phase influence is already small (<0.5 dB at 56 Gbaud). We can conclude that the penalty ΔP_{dB} is primarily set by the intensity response while the equalizer complexity is determined by the phase response.

Using Eq. (1), Fig. 2d shows the impact of the absorption line position on the signal spectrum at 56 Gbaud. Within [-25; +25] GHz of the signal center, ΔP_{dB} and ΔLP_{dB} are constant, but then decrease outside this range. Thus, we deduce that for an absorption line fully overlapping the signal spectrum, its relative position has negligible influence on ΔP_{dB} and ΔLP_{dB}.

We now discuss the optimality of the constant modulus equalizer with molecular absorption. Fig. 3a shows signal spectrum at the equalizer output for 56 Gbaud and for two passes through the cell, together with the ideal minimum-mean-square-error (MMSE) solution[11]. The agreement between both shows that the constant modulus algorithm efficiently converges towards the MMSE solution. Interestingly, the equalizer outputs a distorted spectrum. Thus, the performance can be further increased with a maximum likelihood sequence detector (MLSD) which can resolve the residual inter-symbol interferences (ISI)[11,12]. Fig. 3b shows the reduction in power penalty $\delta(\Delta P_{dB})$ with MLSD (implemented using Viterbi algorithm) performed right before counting errors. Although a significant gain (~2 dB) is obtained at 8.4 Gbaud, we only observe a gain of ~0.25 dB at 56 Gbaud. Indeed, as the symbol rate increases, the residual ISI decreases, and the constant modulus equalizer efficiently mitigates absorption.

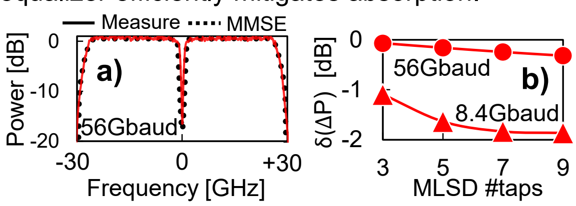

Fig. 3: a) Equalized signal spectrum at 56Gbaud and minimum-mean-square-error solution. b) Decrease in ΔP_{dB} with maximum-likelihood sequence detection, 0 dB reference is with only constant modulus equalizer (Fig. 2b and 2c).

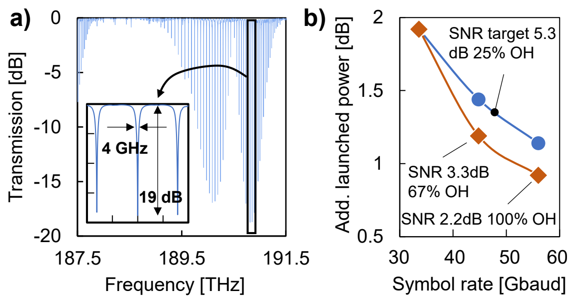

Fig. 4: a) L-band atmosphere transmission spectrum in clear sky, dominated by carbon dioxide[4,5], for a ground to geostationnary satellite link with ~30° elevation[4]. b) Impact of the symbol rate and error correction overhead (OH) on ΔLP_{dB}.

Impact on free space optical system design

We combine the previous results to compute the required additional launched power ΔLP_{dB} for propagation through the atmosphere, using Eq. (1). Fig 4a shows a typical transmission spectrum for a ground to geostationary satellite link over L band[4] consisting of multiple attenuation lines of a variable depths, well fitted with a Lorentz profile (not shown for brevity). We consider a signal impaired by the deepest absorption line of Fig. 4a (width ~4 GHz, depth 19 dB). We emulate absorption digitally (intensity distortion only) and measure ΔP_{dB} without MLSD. α_{dB} is computed offline. Fig. 4b shows ΔLP_{dB} when the symbol rate increases in two cases: 1) Increasing net data rate at unchanged error correction overhead (OH); 2) Increasing OH at unchanged net data rate (100 Gbps). Increasing the OH (redundant bits) allows for correction of more errors after demodulation and the system can operate at a higher uncoded bit error rate (lower target signal-to-noise ratio). The maximum ΔLP_{dB} is obtained at 1.9 dB for 33 Gbaud and 25% OH. From 33 and 56 Gbaud, the ΔLP_{dB} decreases by ~0.78 dB at constant OH. As the signal spectral occupancy increases, fewer signal frequencies are affected by the absorption line. With higher error correction OH, an extra decrease of ~0.22 dB is obtained at 56 Gbaud and 100% OH. Overall, Fig. 4b shows that higher symbol rates and error correction OH increase the robustness to molecular absorption.

Conclusions

We studied the influence of molecular absorption on coherent signals for satellite communications. With digital equalization, we measured limited signal distortions even at large molecular absorption depths, liberating large wavelength windows that would otherwise be precluded (e.g. with legacy intensity detection). We found that signals can be transmitted on worst-case absorption lines of carbon dioxide with 1.9 dB additional launched power at 33 Gbaud but only 0.9 dB at 56 Gbaud. We show that for a given net rate, it is better to operate at higher symbol rate and error correction overhead.

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