

# On the Impact of Gas Line Absorption in Hollow Core Fibers on the Timing Recovery of Coherent Modems

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**Abstract:** We discuss the impact of gas line absorption (GLA) in hollow core fibers (HCFs) on coherent modem timing recovery (TR). The latter is simulated by placing the timing error detector pre- and post-adaptive equalization.

**Keywords:** Hollow Core Fiber, Gas Line Absorption, Timing Recovery.

## I. INTRODUCTION

Coherent optical modems rely on digital signal processing (DSP) to counteract distortions from optical fibers [1]. With the emergence of Hollow Core Fibers (HCFs) [2, 3], a paradigm shift is underway in the telecommunications industry due to their ultra-low latency and reduced nonlinear impairments. Moreover, because the refractive index of air is very close to 1.0 and barely changes with wavelength, the material dispersion is reduced dramatically compared to SMF. The remaining dispersion in HCFs is almost entirely waveguide dispersion, governed by the geometry of the silica capillaries in the cladding, which is relatively low and flat. As coherent modems are adapted for HCF deployment [4], compared to silica-core single-mode fiber (SMF), two challenges surface: 1) Inter-modal interference (IMI) occurs when light scatters between the fundamental mode and higher-order modes due to microscopic imperfections inside the hollow-core fiber and 2) Gas line absorption (GLA) arises when residual gases, primarily  $\text{CO}_2$ , trapped within the hollow core interact with the propagating light at molecular resonance frequencies. The latter creates narrow-band spectral notches with steep phase transitions. According to [5], each absorption line follows a Lorentzian profile with a linewidth on the order of a few GHz at standard temperature and pressure. After aligning the frames between the transmitter (Tx) and receiver (Rx) using pilot symbols, coherent optical modems typically perform a coarse dispersion compensation and timing (or clock) recovery to allow for proper sampling of incoming data. Therefore, it is crucial to understand the impact of IMI and GLA on existing timing recovery (TR) methods, especially as the industry aims to increase the cardinality of the modulation formats to maximize the throughput per wavelength. As shown in Fig. 1, as modulation formats are denser, the end-to-end signal-to-noise ratio (SNR) penalty increases dramatically even at high link SNR (25 dB). This paper is part of a series of studies tackling the fundamental impact of HCFs-specific impairments, combined with other propagation and intrinsic noise sources, on the state-of-the-art coherent modems architectures, especially the interoperable pluggable. Here, we present a simulation-based analysis on how GLA affects the TR subsystem in coherent modems. We focus on analyzing the Godard timing error detector (TED) response to GLA-impaired signals, quantify the resulting jitter, and evaluate the interplay between adaptive equalization (EQ) and performance. It is worth noting that the conclusion is not limited to Godard algorithm. The remainder of this paper is organized as follows: Section II provides background on GLA and the DSP of coherent modems, Section III presents our simulation results and discussion, then we conclude in Section IV.

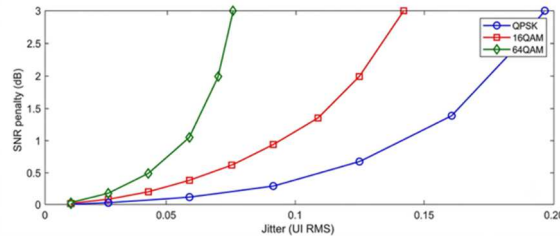


Fig. 1. The impact of untracked jitter for three modulation formats simulated with 3% excess bandwidth.

## II. ON GAS LINE ABSORPTION AND TIMING RECOVERY SUBSYSTEM

HCFs guide light through air or vacuum, reducing nonlinearities and dispersion, but residual gases (e.g., acetylene, hydrogen, water vapor) inside the hollow core create narrow, deep attenuation notches at specific resonant frequencies. These notches can fall within the excess bandwidth, i.e. the spectral edges used by the TED, especially in the L-Band of the optical spectrum. This section presents the relevant background on gas line absorption in hollow core fibers and the digital clock recovery algorithms used in coherent optical receivers.

### A. Sources for GLA in Hollow Core Fibers

The attenuation notches caused by GLA in HCFs can evolve due to multiple physical mechanisms over the fiber's operational lifetime. Slow gas permeation through the cladding and outgassing of structural materials gradually increase the concentration of absorptive species within the hollow core, causing existing spectral notches to deepen and new ones to emerge as the fiber ages. Re-splicing events, whether due to cable cuts or maintenance, introduce a more abrupt degradation mechanism: ambient air, carrying molecules such as CO<sub>2</sub> and water vapor, rushes into the exposed core and becomes permanently trapped, creating sudden and severe localized absorption features. Environmental conditions further modulate these spectral notches on shorter timescales. Temperature variations alter the absorption line shapes through molecular broadening effects. Where elevated temperatures produce wider but shallower notches, while lower temperatures yield narrower and deeper features that are more disruptive to narrowband spectral regions. Collectively, these mechanisms ensure that the spectral profile of GLA in deployed HCF links is neither static nor predictable, presenting a time-varying impairment whose interaction with the signal spectrum directly affects subsystems that rely on spectral symmetry, most notably the TR loop.

### B. Discussion on DSP and Timing Recovery in Coherent Modems

The Godard algorithm relies on correlating upper and lower sidebands of the signal spectrum around the half-baud frequency. If GLA attenuates these critical excess bandwidth regions, the timing error signal degrades, potentially preventing the receiver from acquiring or maintaining clock synchronization. This vulnerability arises because the timing error detector gain is proportional to the signal energy in the excess bandwidth, and GLA-induced loss directly reduces this energy. The Godard timing error estimate is calculated in the frequency domain as follows:

$$\hat{\tau}_{err} = \sum_{k=\frac{(1-\beta)}{2}(\frac{N}{2})}^{\frac{(1+\beta)}{2}(\frac{N}{2}-1)} \text{Im}\{r_k r_{k+N/2}^*\} \quad (1)$$

where  $\tilde{r}_k$  is the  $k$ -th DFT coefficient of the received signal,  $N$  is the DFT size,  $\beta$  is the roll-off factor, and  $(\cdot)^*$  denotes complex conjugation.

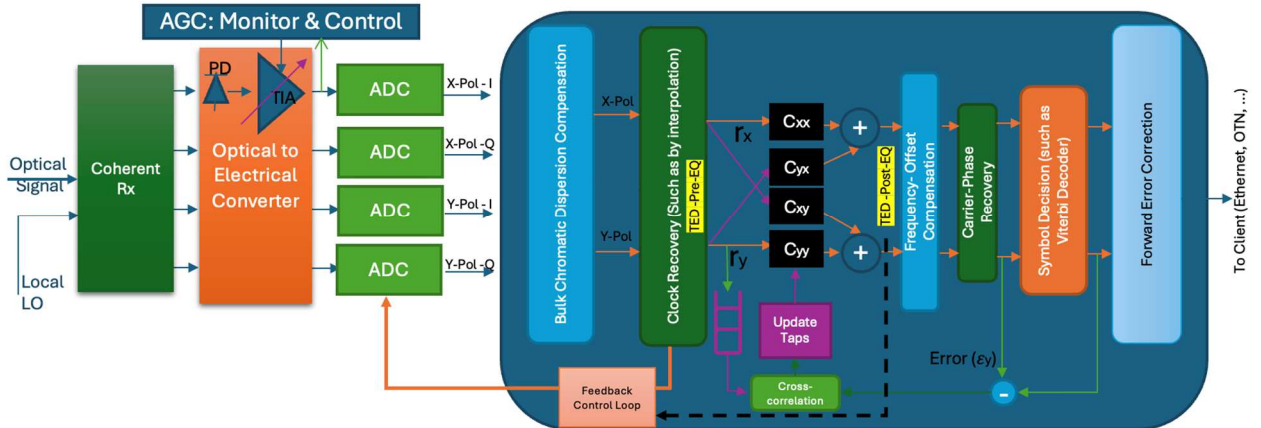


Fig. 2. Building blocks of a coherent optical receiver spanning electro-optics, data converters and signal processing.

Fig. 2 shows the TR control loop, which is fundamentally constrained by the feedback latency. The cumulative delay typically spans the equivalent of hundreds of symbol periods at 118GBaud, encompassing the TED computation, pipeline buffering, and the subsequent actuation of the analog-to-digital converter (ADC) sampling clock or digital fractional delay filter. Therefore, there is a strict upper bound on the achievable loop bandwidth to maintain adequate phase margin and prevent oscillatory instability, practically limiting the TR tracking bandwidth to 500 kHz to 1 MHz. Consequently, high-frequency timing jitter components, such as those induced by Equalization Enhanced Phase Noise (EPPN), which exhibit significant spectral power density extending from 1 MHz to beyond 10 MHz, fall well outside the unity-gain crossover frequency of the feedback loop. Because the control loop cannot dynamically track and suppress these fast-varying perturbations, the residual high-frequency jitter manifests as uncompensated sampling instant misalignment. Since HCFs have lower CD, compared to SMFs, it is expected that the EPPN noise power will scale down linearly with compensated CD, and therefore less constraint is imposed on high-frequency tracking. That being said, the multi-service agreement by Optical Internetworking Forum (OIF), for the ZR+ solution, suggests using two Frequency Division Multiplexing (FDM) subcarriers to reduce the effect of EPPN by half. Other impairments, such as the interaction of polarization mode dispersion (PMD) and polarization dependent loss (PDL), create dynamic changes in both the amplitude and the phase of the spectrum in the frequency response. Due to its stochastic nature, such interaction is compensated, along with changes in the state of polarization, by the EQ using the Least-Mean-Square (LMS) method, implemented as  $2 \times 2$  filters with taps called  $C_{xx}$ ,  $C_{xy}$ ,  $C_{yx}$  and  $C_{yy}$ .

### III. RESULTS AND DISCUSSIONS

This simulation compares the impact of GLA-induced jitter, when corrupting the frequency bins used by the TED, before EQ as is typically the case versus after the EQ in a dual-polarization 16QAM coherent system operating at 118Gbaud. The pulse-shaping roll-off of  $\beta$  was set to 0.07 and the frequency-domain block was formed by 1024-point DFT. The channel model between the Tx and Rx is set to operate at 17 dB SNR, modeled as Additive White Gaussian Noise (AWGN) and equivalent to the link budget limit of 800ZR defined by the OIF, and per-block AGC normalizing to a target RMS modeling an ADC of 8-bit. The roll-off  $\beta$ , for a fixed DFT-size, governs the number of frequency bins that can be used in eq. 1. The latest commercial embedded coherent modems operate at even lower than 0.07 to maximize spectral efficiency especially for submarine cables. However, the OIF multi-service agreement allows for up to 20% excess bandwidth for the pulse shaping. The channel model applies frequency-selective attenuation (0–16 dB), equivalent to one span of 80 km with GLA of 0.2 dB/km, to both the primary and shifted Godard bins simultaneously. The 2x2 EQ, applied after the matched filter, aims to normalize the frequency response within its dynamic range by converging to the inverse of the HCF's channel response. While it restores the signal amplitude, it amplifies the accumulated noise, up to that point, in those bins by the same factor and hence, introducing a noise enhancement penalty. The simulation results are shown in Fig. 3, with jitter quantified in dB based on the variance of the timing estimates. When less than 12 frequency bins are impacted, both capturing TED in “pre-EQ” or “post-EQ” are degrading in the range of 2 dB. To put this into perspective, an increase of  $\sim 7$  dB in jitter, while limiting the SNR penalty to 1 dB, means that the modem can support 16QAM instead of 64QAM (A reduction of throughput by 33.3%). It is notable that when most or all of the Godard bins are attenuated ( $\geq 26$  bins), the EQ provides up to 7.57 dB of jitter improvement because restoring the timing tone dominates over the noise penalty. Without equalization, the estimator effectively runs on noise alone (jitter degrading to  $-22.6$  dB), whereas with EQ the timing tone is recovered and jitter saturates at approximately  $-30$  dB, limited by the amplified noise. Therefore, in the presence of GLA and considering only the TR penalty, 16QAM/32QAM/64QAM are not achievable. From equalization perspective, which is not tackled here, it is worth noting that since the notches caused by GLA vary slowly over time, as discussed in Section II, it would be beneficial to slowly move their compensation to the static, same taps performing CD compensation in Fig. 2, thereby freeing the dynamic range of the EQ so it compensates for the dynamic ripples across the spectrum.

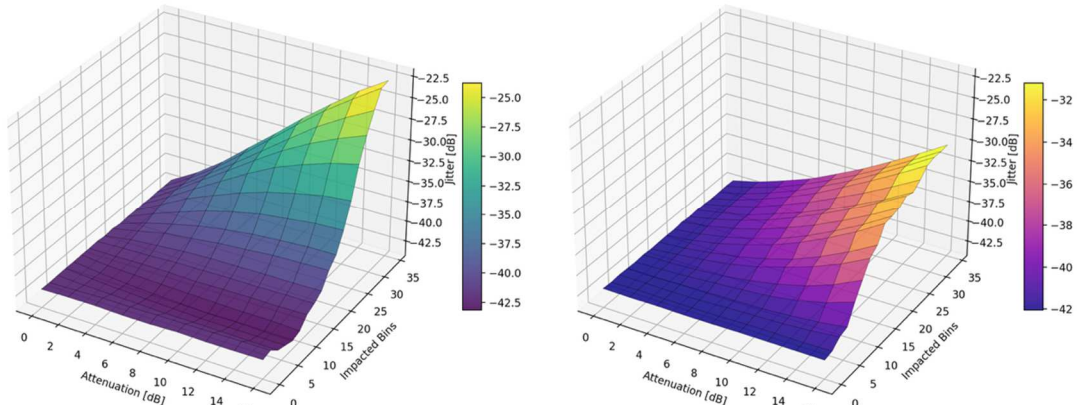


Fig. 3. Simulation comparing measuring jitter due to GLA before (on the left) and after adaptive equalization in coherent receiver (on the right).

### IV. CONCLUSIONS

To fully leverage HCFs, especially in the L-Band where the modem and optical ecosystem is mature, we simulated the impact of GLA on the TR of coherent optical modems. Our results show that for TEDs such as Godard and Gardner, which use frequency-bin components at the spectral edges, GLA-induced notches introduce significant timing jitter, with jitter power increasing proportionally with absorption depth. Furthermore, we demonstrated that measuring the timing error after the adaptive equalizer reduces jitter by approximately 8 dB when the spectrum is heavily impacted by GLA. These findings highlight the need for GLA-aware TR design and underscore the limitations imposed on achievable modulation order and throughput.

### REFERENCES

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