Experimental Evaluation of Commercial OTN Transceivers under Emulated Weak Turbulence

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***Abstract*—In next-generation networks, the integration of satellite network segments within the existing terrestrial ones represents a key element to deliver high-speed connectivity with increased coverage, scalability, and reliability. The development of optical satellite links could be eased by taking advantage of the mature technology deployed in fiber-based networks. Differently from fiber optics propagation, laser beams traveling across the atmosphere experience turbulence-induced fading. Considering that commercial hardware has been designed to work in the static fiber channel, degradation of the communication performance is expected when the same devices are employed in scintillation-affected links. We present the first experimental performance assessment of commercial Optical Transport Network (OTN) equipment under the effect of scintillation. Our study focuses on a pre-amplified receiver employing coherent 100G and IM/DD 10G transceivers. We setup a testbed that emulates weak turbulence, reproducing the scintillation statistics at the receiver typical of feeder links. Our results highlight differences between 100G coherent and 10G IM/DD transceivers in terms of reliability, providing insights for hardware optimization and network design in future optical feeder links systems.**

Keywords—Free Space Optics, Optical Feeder Link, Fading Emulator, Commercial Hardware

I. Introduction

In satellite networks, the massive spread of bandwidth-hungry services pushes Radio Frequency (RF) wireless systems on the verge of their physical limits. Thus, Free Space Optics (FSO) communications are poised to revolutionize satellite links, fostering also the integration with terrestrial networks and enabling a high-speed connectivity with unprecedented data rates [1]. As current fiber networks are based on OTN standard, this is a natural choice for FSO in space. Therefore, coherent modulations, such as Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK), are considered for optical inter-satellite links and optical feeder links (OFLs) [2], [3]. Nonetheless, 10 Gb/s solutions – based on intensity modulation/direct detection (IM/DD) – are suitable for low-cost and resource-constrained missions [2].

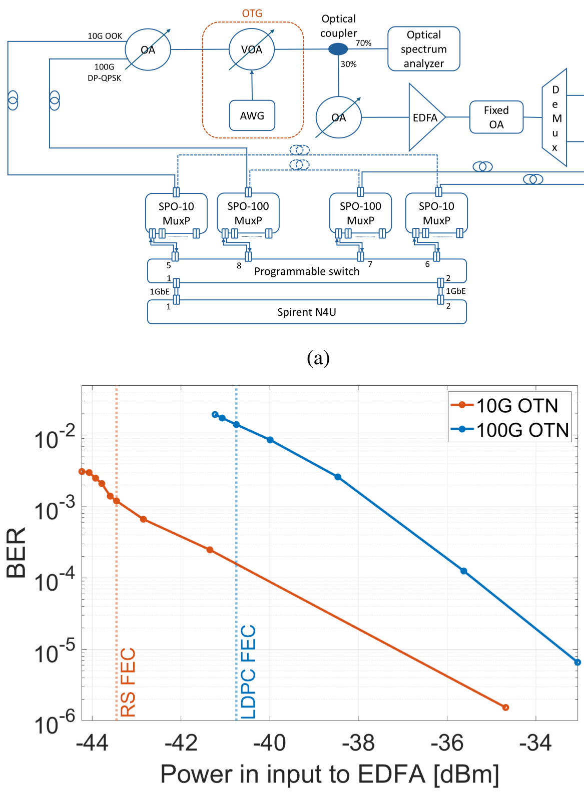
Today, extensive testing of commercial equipment is necessary to verify their reliability in space links. Indeed, key differences distinguish the static fiber channel from the FSO one, where the instantaneous received power is an unpredictable random quantity, mainly due to the atmospheric turbulence. Due to the long turbulence-induced scintillation timescale (i.e., from 1 to 10 ms [4]) compared to the bit duration, frame losses are experienced. A previous research investigated the recovery times of commercial equipment in response to emulated deep fading events, considering 10 Gb/s (10G), 100 Gb/s (100G), and 10G Ethernet transceivers [5]. Subsequent studies experimentally assessed packet loss and response time jitter in an emulated downlink OFL using 10G Ethernet [6], [7].

In this work, we present the first experimental comparison of pre-amplified OFLs employing coherent 100G and IM/DD 10G OTN transceivers. To this aim, we initially set up a testbed that emulates the links under atmospheric weak turbulence, accurately reproducing the scintillation statistics typical of OFLs to the received optical power. We measured the frame losses of both transceivers under different turbulence strengths, providing valuable insights into the power requirements for achieving the desired link availability, guiding the design of future space networks.

II. Experimental setup

To assess the performance of commercial transceivers, we set up the testbed shown in Fig. 1a. A Spirent N4U traffic generator and analyzer, featuring 1 Gigabit Ethernet (GbE) interfaces, generates one Ethernet frame every µs. A programmable switch keeps the Spirent interfaces always on during the experimental tests, and it is configured to properly forward the frames from input to output ports. The switch is alternatively connected to two pairs of commercial 10G and 100G muxponders, necessary to test OTN-based equipment. The 100G transceiver (at $1544.53\,\mathrm{nm}$) uses DP-QPSK, while the 10G transceiver (at $1545.32\,\mathrm{nm}$) employs On-Off Keying (OOK) modulation. The signal from the 10G (or 100G) link is controlled by a Variable Optical Attenuator (VOA) to ensure consistent input power at the Optical Turbulence Generator (OTG) in both configurations. The signal then undergoes fading, generated by an OTG made by a voltage-controlled VOA, which dynamically drove the power output of the OTG, reproducing the desired time series. To operate the VOA, we

978-3-903176-67-6



(a)

(b)

Fig. 1: (a) Experimental testbed. VOA: Variable Optical Attenuator; AWG: Arbitrary Waveform Generator; EDFA: Erbium-Doped Fiber Amplifier; MuxP: muxponder; (b) pre-FEC BER vs. EDFA input power for 10G (orange curve) and 100G (blue curve) links. Sensitivity thresholds are highlighted.

used an Arbitrary Waveform Generator (AWG) controlled by MATLAB. The VOA output goes through a 30:70 coupler, whose 70% output is sent to an optical spectrum analyzer. Instead, the 30% output is connected to a manual VOA to adjust the average optical input power of the low-noise Erbium-Doped Fiber Amplifier (EDFA). The amplified signal is attenuated to avoid transceiver saturation and then sent to the demultiplexer and receiver. During the transmission, the Spirent counts the number of transmitted and received frames, so that the number of dropped frames can be determined.

First, we measured the sensitivity of the pre-amplified receivers. In the testbed, we measured the pre-Forward Error Correction (FEC) bit error rate (BER) of both 10G and 100G links using the Spirent, versus the EDFA input power levels. The results are reported in Fig. 1b, and allow us to evaluate the transceivers sensitivities, i.e., the lower EDFA input powers at which no errors occur after the FEC decoding. As known, OTN transceivers already include FEC, specifically, Reed-Solomon (RS) for the OOK and Low-Densitiy Parity-Check (LDPC) for DP-QPSK. As a result, the two links have different FEC thresholds, i.e., 10^{-3} for OOK and 10^{-2} for DP-QPSK. We obtained the sensitivities of -43.5 dBm and -40.7 dBm for 10G and 100G links, respectively; these correspond to 11.4 dB and 14.2 dB of Optical Signal-to-Noise Ratio (OSNR) at the EDFA output. As expected, the 10G link has better sensitivity and requires a lower OSNR to achieve *error-free* communication. In comparison, the 100G link requires 2.8 dB more power to attain the same BER performance.

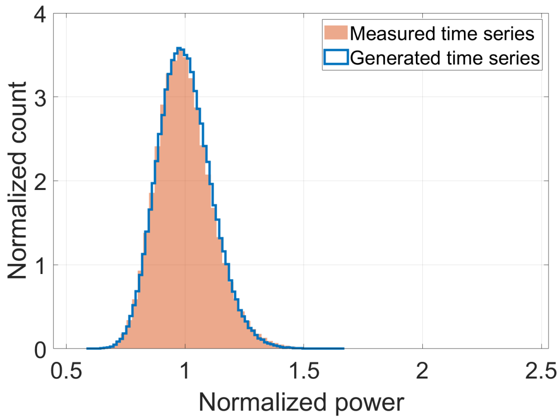
We also characterized the VOA, used to vary the instantaneous received power, mimicking real-world variations. The VOA, operating over the whole C-band, was characterized by measuring its attenuation vs control voltage curve, ranging from 0 V to 6.5 V (0.1 V step), at both transceivers central wavelengths. This process revealed wavelength-independent outcomes, with attenuation values ranging from 5.3 dB (at 0 V) to 51.4 dB (at 6.5 V). However, a nonlinear increase of the VOA attenuation with control voltage was observed. To accurately reproduce the desired attenuation values, we computed the inverse function of the measured VOA characteristic through shape-preserving piecewise cubic interpolation. This allows us to easily determine the proper control voltage for any desired attenuation. The linearization process achieved an R-squared value of 0.99. Additionally, we measured the VOA frequency response, estimating a 3-dB bandwidth of around 500 Hz. Due to the limited bandwidth and to the time series sampling frequency, a pre-distortion of the control voltage time-series was necessary to ensure that the generated power distribution matched the desired Probability Density Function (PDF). As an example, Fig. 2a demonstrates the accurate match between the measured optical power at the EDFA input and the computed one when the scintillation index is set to $\sigma_I^2 = 0.1$.

III. Results

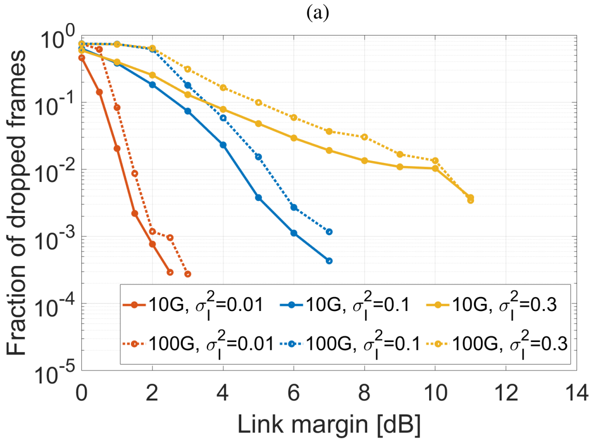
We experimentally evaluate the emulated OFLs using commercial transceivers under emulated scintillation. We considered a wide range of scintillation indexes σ_I^2, i.e., 0.01, 0.1, and 0.3 and the three corresponding time series, consisting of 3×10^5 samples. These were randomly generated based on a lognormal PDF, which is widely accepted for weak turbulence scenarios. It is also used in moderate-to-strong turbulence regimes when aperture averaging applies at the receiver telescope, e.g., the case of downlink OFLs [4]. For each σ_I^2, we generated a time series, sampled at the Greenwood time constant, defined as the time interval over which turbulence remains essentially unchanged [4]. We assumed a Greenwood time interval of 1 ms, resulting in a time series duration of 5 min. As an example, this value and $\sigma_I^2 = 0.01$ are representative of an aperture-averaged downlink transmission from a LEO satellite at 800 km. Indeed, at 1.55 µm and 30° elevation, such values approximately correspond to a refractive index structure parameter at ground equal to 1.17×10^{-13} $m^{-2/3}$ and a ground wind speed of 8 m/s.

Except for scintillation, turbulence induces phase degradation and minor depolarization [4], [8], which could potentially affect coherent transmissions. However, the transceiver DSP performs operations such as carrier phase estimation and polarization recovery, which allow us to neglect these effects.

First, the 10G and 100G links were individually tested in the testbed. Each test lasted seven minutes, over which the Spirent was configured to continuously generate Ethernet frames (total around 4×10^8 frames). In the first five minutes, one of the three randomly generated fading time series was applied. Namely, for a given scintillation index, the same lognormally distributed attenuation pattern was used for both links. Instead, in the last two minutes the attenuation emulating the fading was removed, so that the link had the possibility to recover from fading. For each time series and transceiver type, we measured the dropped frames as a function of the link



(a)



(b)

Fig. 2: (a) Histograms of the generated and measured time series at $\sigma_I^2 = 0.1$. (b) Fraction of dropped frames vs. link margin (i.e., the difference between the mean EDFA input power and the receiver sensitivity) for the 10G (solid lines) and 100G (dashed lines) links.

margin by setting the average received power at the input of the EDFA to correspond to each transceiver sensitivity, along with an additional (variable) margin value. This implies that, due to the difference in sensitivity, the same link margin value is associated to different EDFA input powers in the two links.

The results are depicted in Fig. 2b for both the 10G (solid lines) and 100G (dashed lines) links, for the three σ_I^2. We note that, by considering 1 ms as Greenwood time interval, both transceivers recovery times are dominated by the OTN failure detection protocols [5]. We see that the 100G link is more susceptible to fading-induced performance degradation compared to the 10G link, even if the maximum attenuation is limited to few dBs. This result is attributable to DSP operations. Moreover, at 0 dB link margins, both transceivers experienced frequent outages; however, the 100G required longer to recover compared to 10G. This resulted in a percentage of dropped frames of 75% for all scintillation conditions for the 100G, and comprised between the 46% and 63% for the 10G. When comparing 100G and 10G link performance, the 100G link exhibits a factor (on average) of 2.6× at $\sigma_I^2 = 0.01$, 2.3× at $\sigma_I^2 = 0.1$, and 1.7× at $\sigma_I^2 = 0.3$ in terms of dropped frames. Thus, the differences in performance between the two transceivers reduce as the turbulence strength increases.

To achieve a certain level of reliability, for example 1% of losses, the 10G and 100G require margins of 1.1 dB and 1.5 dB for $\sigma_I^2 = 0.01$, 4.5 dB and 5.2 dB for $\sigma_I^2 = 0.1$, and 9 dB and 10.2 dB for $\sigma_I^2 = 0.3$, respectively. Thus, as expected, the required margin increases with the scintillation index and is higher for the 100G link. Finally, we stress that to obtain the same performance of the two links in terms of dropped frames, the additional power for the 100G must take into account also the difference in sensitivity.

IV. Conclusion

We introduced an experimental technique to emulate the impact of turbulence in a FSO link and performed the first experimental comparison of links based on two types of OTN transceivers (100G coherent and 10G IM/DD). We emulated a low turbulence scenario and assessed how it can negatively impact on performance: particularly, for coherent solutions with DSP, higher margins are needed to properly reduce the probability of packet loss. The 100G link is found to be more vulnerable to fading-induced errors and requires an increase in link margin to maintain similar reliability performance.

These results provide valuable insights for the design and optimization of future OFL systems and network equipment operating under atmospheric conditions. Clearly, further investigations should be devoted to assess the effect of strong turbulence as well as experimentally test the conditions with even lower probability of outage, than those emulated here. Specifically, future work could involve the use of more advanced fading time-series, modeling strong turbulence (e.g., gamma-gamma PDF) and better representing the scintillation frequency response by means of spectral shaping.

Acknowledgements

This work was partially supported by the European Union - Next Generation EU under the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.3, CUP J53C22003120001, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART").

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