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Experimental assessment of various optical communication chains for high-capacity optical feeder links

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ABSTRACT

Optical feeder links (OFL) are expected to become part of future Very High Throughput Satellite (VHTS) systems in response to the growing demand for higher capacity and lower costs. H2020 VERTIGO (Very High Throughput Satellite Ground Optical Link) project was set to prove key optical communication technologies and to address: 1) Throughput increase with high spectral and power efficiencies. 2) Higher optical power generation and delivery. 3) Atmospheric turbulence mitigation by optical and digital processing.

Transmit and receive optical communication models were developed in rack units for assessing, in laboratory and outdoor trials, their intrinsic performance, robustness against atmospheric turbulence and compatibility with other technologies. The models for 25 Gbps OOK/DPSK and RF analog modulation with optically pre-amplified direct or differential detection are reported with the achieved performance. An atmospheric channel emulator fed with time series established by simulations was used to mimic the propagation losses and fading of the optical signal coupled into the receiver. Both the downlink and uplink under weak or strong turbulence were emulated. For digital transmission experiments, the performance metrics include BER curves, detection sensitivity and power penalty. State-of-the-art sensitivities were achieved especially under 25 Gbps DPSK. For RF analog transmission, the performance metrics were constellation diagrams and Error Vector Magnitude (EVM) measured for various modulations from QPSK to 64-QAM. Are reported the results of optical transmission experiments first performed in the laboratory under static and dynamic propagation channels, then in the outdoor trial successfully carried out in July between Jungfraujoch and Zimmerwald in Switzerland.

Keywords: Free Space Optical (FSO) communications, Optical feeder links (OFL), DPSK, satellite communications, VERTIGO, demonstration

1. INTRODUCTION

Optical feeder links are expected to become an essential part of future Very High Throughput Satellite (VHTS) solutions. They are a promising technology to complement conventional RF solutions offering the inherent advantages of optics (wide bandwidth, no frequency regulation, low beam divergence, restistance to jamming) in the face of growing demand for higher capacity and lower costs.

VERTIGO (Very High Throughput Satellite Ground Optical Link) is a H2020 project to prove the critical optical communication link technologies in ground demonstrations [1]. VERTIGO addresses the following challenges on the road to optical feeder links: 1) Throughput increase through advanced modulation and detection schemes for high spectral and power efficiencies. 2) Generation of higher optical power by amplifier enhancement and also via incoherent/coherent beam combining. 3) Optical and digital processing techniques for mitigation of atmospheric propagation impairments.

In the past, several experiments already proved the feasibility of FSO links, achieving records in terms capacity and symbol rate [2-5], implementing realistic prototypes [6] or looking for advanced concepts [7]. Yet, to the best of our knowledge, there was no demonstration which gathered all the critical building blocks for an Optical Feeder Link (OFL).

In VERTIGO project, Thales Alenia Space conducted the overall system definition and design. ONERA provided among others an Optical Ground Station mockup including an adaptive optics system while Thales Alenia Space (in Switzerland) provided the Space Terminal emulator. Thales Alenia Space (in France) developed optical communication breadboards for experimental assessment in laboratory test-beds and in an outdoor trial, not only for their intrinsic performance but also for their robustness against atmospheric propagation and compatibility with other enabling technologies. They implement various modulation formats and detection techniques including 25 Gbps OOK and DPSK, 50 Gbps DQPSK and analog RF modulation, with optically pre-amplified direct or differential detection.

Hereafter are presented the optical communication breadboards developed by Thales Alenia Space within VERTIGO and experimental results obtained in the laboratory with a free-space optical propagation channel emulator as well as in the outdoor transmission trial which took place in July between Jungfraujoch and Zimmerwald in Switzerland.

2. OPTICAL COMMUNICATION BREADBOARDS

The optical communication boards developed by Thales Alenia Space within the framework of the H2020 VERTIGO project have been designed to meet certain objectives and to comply a number of constraints. Breadboards had to be implemented with mature and commercially available devices very similar as those that could be integrated into operational systems in the near term. They had to be transportable and quick to set up pin order to facilitate the demonstrations.

They were first tested in TAS facilities in Toulouse to determine their nominal behavior and to establish performance of reference. They were then shipped to Switzerland and installed at the two sites of Jungfraujoch and Zimmerwald selected for the outdoor demonstration. A last laboratory demonstration and evaluation campaign should take place at TRT in Palaiseau for the integration and assessment of high-power sub-systems.

In all these experiments, attention is paid to the performances but also to the impact of the transmission such as the optical channel crosstalk, the stability in time and the robustness against the free space propagation channel, especially the synchronization loss.

Fig. 1 below gives an overview of the experimental transmission set-up. The optical layer is composed of a narrow-linewidth (about 80 kHz) CW laser, modulation and demodulation units that will be described in the next sections, a commercial High Power Optical Amplifier (HPOA) at the transmit side and a Low Noise Optical Amplifier (LNOA) at the receive side. The LNOA has two stages of amplification, a small-signal gain higher than 45 dB and a noise figure (NF) lower than 4.2 dB. Up to 4 optical channels can be multiplexed per modulation unit, and up to 8 optical channels can be switched on simultaneously on a 100 GHz grid. Operating wavelength is roughly between 1540 and 1560 nm. An input power monitoring unit has been developed to measure and acquire the received optical power between -57 and -10 dBm.

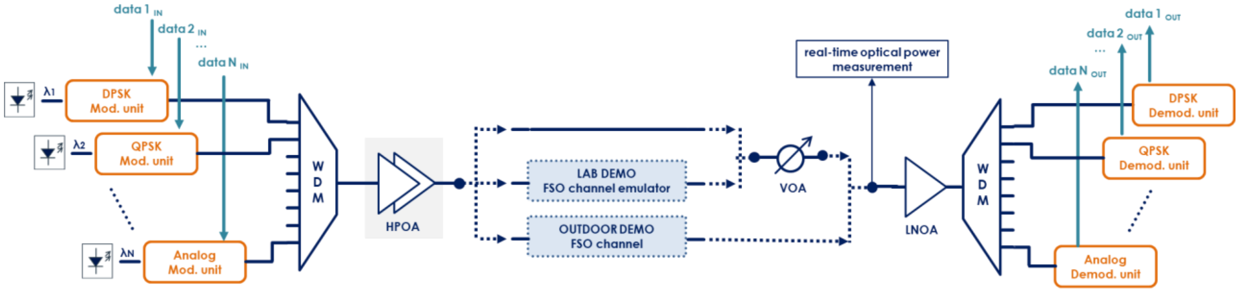


Figure 1. Overview of VERTIGO transmission scheme

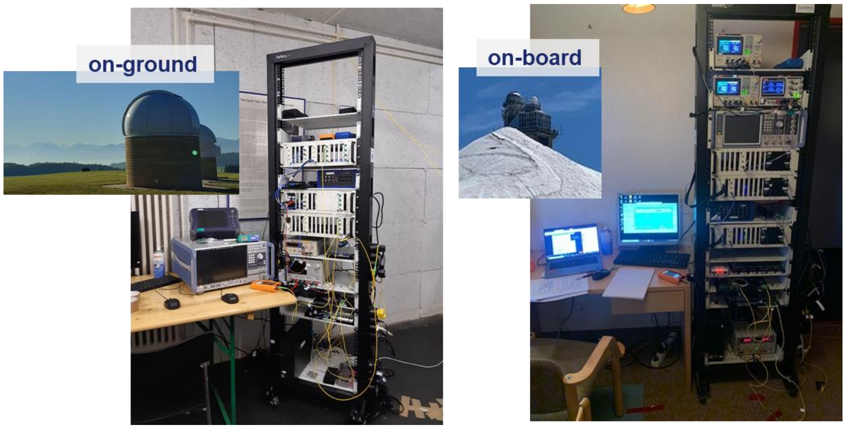


Figure 2. Optical communication rack assemblies developed within VERTIGO

An outlook of the optical communication rack assemblies developed by Thales Alenia Space within VERTIGO is shown on the picture of Fig. 2 above. All of the modulation and demodulation units are placed into rack units with all the optical, data and DC supply interfaces on the front panel.

OOK, DPSK and DQPSK modulation formats have been implemented, all working at 25 Gbd. OOK and DPSK transmitters are based on commercial Mach-Zehnder modulators (MZM) with their driver and bias controller. Driver RF bandwidth is the limiting factor, about 18 GHz for OOK and 23 GHz for DPSK. DQPSK transmitter is based on Indium Phosphide MZM co-packaged with linear RF drivers. Data is provided by a Pulse Pattern Generator sending standard PRBS sequences.

At the receive side, OOK demodulation units are simply composed of a photoreceiver. 10G and 25G links having their dedicated receivers with the corresponding electro-optical bandwidth. For DPSK; the receive unit uses a delay line interferometer (DLI) demodulator and a balanced dual-detector receiver. More details are given in [8]. DQPSK demodulation unit uses a custom demodulator and two balanced dual-detector receivers. Demodulation units are then connected to a Bit Error Ratio (BER) Tester (BER-T) that counts the number of errors during 1 second. The BER-T has an internal clock recovery unit.

RF transmitter is also based on commercial Mach-Zehnder modulators (MZM) and a ditherless modulator bias controller. The RF optical receiver features a C-band (~5 GHz) RF bandpass filter associated to a C-band photodetector. Data is generated by a vector signal generator from Rohde & Schwarz and analyzed by the reference FSW from Rohde & Schwarz equipped with the option K70 that allows for constellation analysis.

3. LABORATORY OPTICAL TRANSMISSION EXPERIMENTS

3.1 Free space optical propagation emulation and assessment

An emulator of the FSO propagation channel was considered mandatory to mimic atmospheric turbulences. Several approaches have already been implemented depending on the effect to be studied [9-13]. An all-fiber approach was chosen for creating amplitude and phase dynamic variations. The two modulators are controlled by an Arbitrary Waveform Generator (AWG) and a computer. They can be fed with various time series either from simulations or from measurement. Here, simulations from ONERA were used representing a GEO application with 25 and 60 cm aperture telescopes, respectively onboard and on the ground, 2 elevation angles (30 and 40°), 2 turbulence regimes (weak and strong) and correction by adaptive optics (AO) on both directions (pre-compensation at emission of uplink and correction at reception of downlink), assuming a mono-mode Gaussian reception and emission. The AO corrected propagation channel [14][15][17] exhibits amplitude as well as phase noise fluctuations [18]. Amplitude and phase variations can be emulated together or separately. Hereafter are presented amplitude emulation for a downlink and an uplink with strong turbulences.

The two time series are shown in Fig.3 below. It is well known that AO correction is less efficient on uplink due to point ahead anisoplanatism (see [14][15][17] and references therein). AO pre-compensated uplink is therefore more affected by the propagation through turbulence than the AO corrected downlink, as it can be clearly seen in Fig.3.

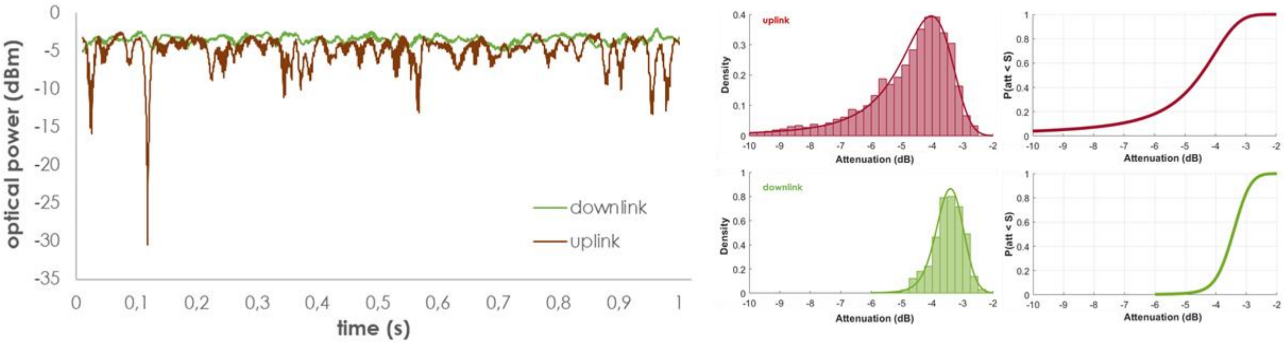


Figure 3. Time series for downlink and uplink under strong turbulence and with AO correction

The FSO channel emulator was validated for each of the time series by measuring the actual optical output power. The offset between the expected and the actual optical output power was always below 1 dB.

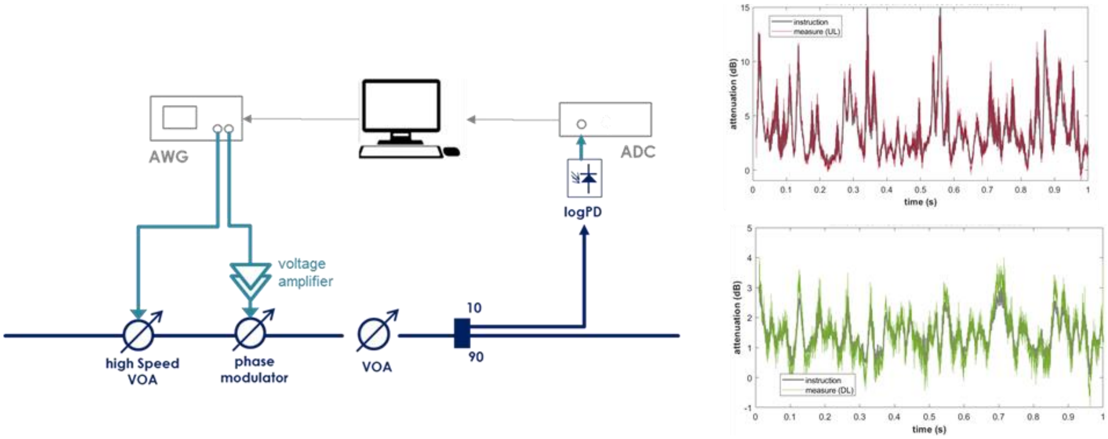


Figure 4. Schematic (left) of the laboratory FSO channel emulator and validation (right) of implementation in amplitude

The impact of the FSO propagation channel was assessed by measuring the penalty induced by the emulator in a dynamic regime. This penalty is obtained by comparing the performance (for instance detection sensitivity in digital transmission) with and without the emulator. The configuration without turbulence is called back-to-back.

3.2 Digital transmission experiments

For digital optical links, the transmission performance metrics were the BER curve, i.e. bit error rate vs. received optical power (ROP) and detection sensitivity defined as ROP required for 10^{-3} BER.

Back-to-back sensitivities are shown in Fig.5 below (for PRBS15 and no FEC). Sensitivities at the state-of-the-art were achieved, e.g. 17 photons per bit under 25 Gbps DPSK.

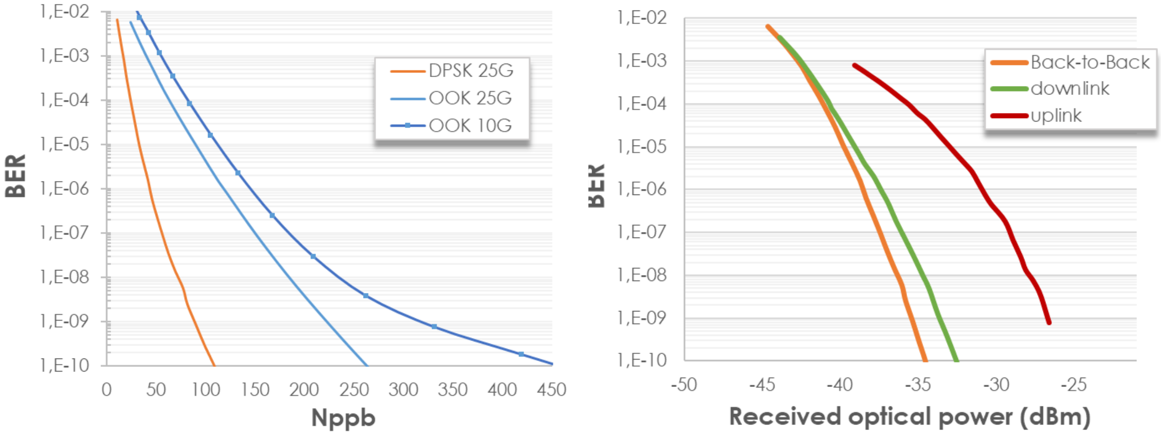


Figure 5. (a) back-to-back BER as a function of the number of photons per bit (Nppb) for OOK 10 and 25G and DPSK 25G (b) assessment of FSO transmission penalty for DPSK 25G

Table 1. Detection sensitivity penalty due to turbulences along the downlink and the uplink

	10^{-3} BER		**10^{-6} BER**	
Modulation	**Uplink**	**Downlink**	**Uplink**	**Downlink**
OOK 10 G	7.2 dB	1.5 dB	9.7 dB	1.35
OOK 25G	2.9 dB	0.2 dB	7.05 dB	0.45 dB
DPSK 25G	3.2 dB	0.2 dB	7.65 dB	1.15 dB

The power penalty induced by the free space optical channel emulator is defined as the difference in detection sensitivity, i.e. in received optical power required for a given BER. Fig. 5 (b) is an example of DPSK 25G transmission results for a downlink and for an uplink under strong turbulences. Detection sensitivity penalties are summarized in Table 1 above. Downlink is less affected by turbulences and presents lower power penalties than the uplink. For all the modulation formats, the penalty increases when the BER decreases (and the received input power increases).

3.3 RF analog transmission experiments

For the RF analog links, the transmission performance metrics were constellation diagrams and Error Vector Magnitude (EVM) vs. ROP; they were measured for five modulation formats from QPSK to 32-QAM and at two symbol rates (240 and 600 Mbd).

Fig. 6 below presents the constellation diagrams for several received optical powers in back-to-back configurations. EVM were similar for all the modulation formats. Impact of the FSO propagation channel is shown on Fig. 7, for 600 Mbd QPSK and 16-QAM, both for uplink and downlink. Very similar power thresholds were found to reach an EVM of 14% (corresponding approximately to a SNR of 17 dB), namely about -44 dBm for the uplink and -53 dBm for the downlink. Fig.7(b) gives the BER estimated from the EVM measurements showing that very low BER ($<10^{-10}$) before FEC could be achieved for both directions. 16-QAM requires a higher ROP than QPSK for a given BER and suffers from BER degradation at high ROP due to receiver saturation.

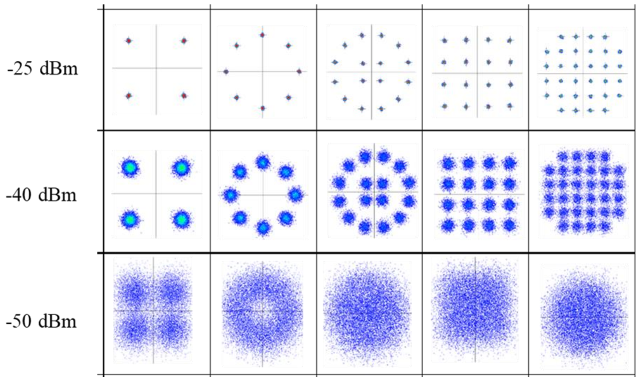
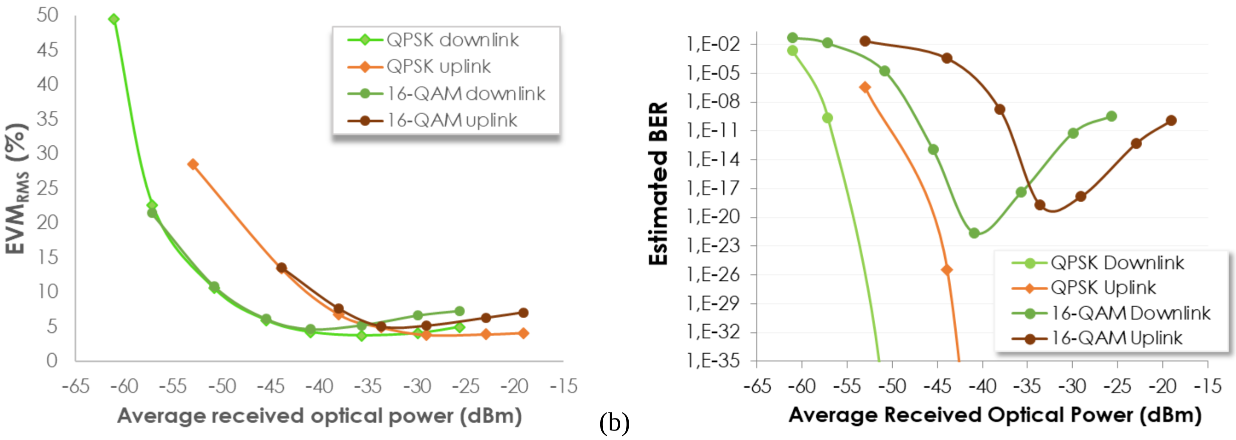


Figure 6. Constellation diagrams vs. ROP for several modulation formats at 600 Mbd



(a) (b)

Figure 7. EVM (a) and estimated BER (b) vs. ROP for 600 Mbd QPSK and 16-QAM with strong turbulence along the uplink and the downlink

4. OUTDOOR FREE SPACE OPTICAL TRANSMISSION TRIAL

4.1 Free space optical link overview

Following these first laboratory results, an outdoor FSO transmission trial was organized to perform real end-to-end system tests. The outdoor demonstration took place in Switzerland in July 2022. The optical link was 53 km long between the Jungfraujoch High-Altitude Research Station, 3700m above sea level, and the Zimmerwald Observatory, 900m above sea level, presenting 3° elevation angle. This line of sight is demanding: very long distance, an optical axis that stays essentially within 1000 m above ground together with a complex geographical topology (mountains, lakes, and lowlands near Bern). Scintillation was therefore expected to be much stronger than in the laboratory simulations. A first hint of the observing conditions is given by the meteorological data. At Jungfraujoch, winds speed was between 5.6 and 11.2 m.s^{-1} and temperatures approximately between 4 and 8°C. At Zimmerwald, winds speed was below 1.7m.s^{-1} and temperatures between 12 to 24 °C. Note that AO data are currently processed by the ONERA team and will allow a quantitative characterization of the turbulence conditions on the line of sight (see an example of application to FEEDELIO demonstration data in [14, 15]).

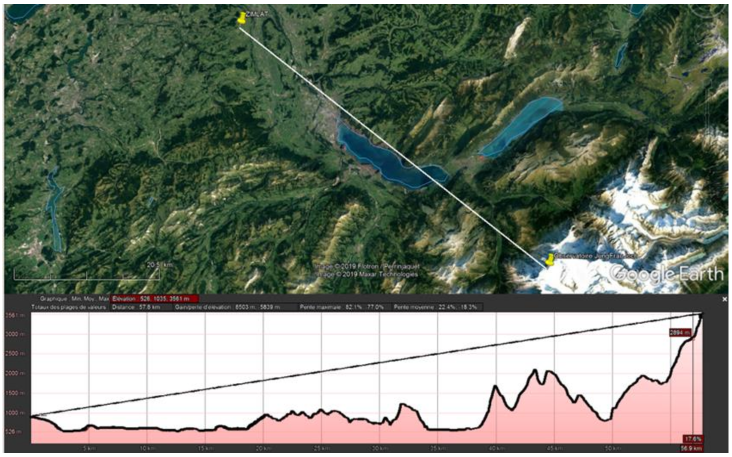


Figure 8. Topology of VERTIGO’s outdoor transmission trial

Jungfraujoch High-Altitude Research Station was playing the role of the GEO satellite. Thales Alenia Space (Switzerland) provided the space terminal, including a 5cm aperture telescope. The Optical Ground Station (OGS) mockup was provided and operated by ONERA [14,15] and installed at Zimmerwald observatory. The OGS was composed of a 35cm aperture telescope and an AO system including a deformable mirror, a Shack-Hartmann wavefront sensor with 8x8 sub-apertures and a real-time computer. The optical communication units were separated from telescopes by several meters at Jungfraujoch facilities and tens of meters at Zimmerwald. Thales Alenia Space (France) brought the communication units described in the previous sections and ETHZ coherent modulation units. The total output power was limited by eye-safety regulation.

Hereafter are reported the results of downlink FSO transmission experiments corresponding to a worst case of a link from the space terminal to an OGS.

4.2 Results of outdoor transmission experiments

For this experiment, the variations of the received optical power (at the LNOA input) were recorded in addition to the performance measurement presented above. An example is shown in Fig. 9 below. From this data, some statistics have been extracted such as the cumulative density function (CDF), occurrences and duration of fadings, mean and averaged optical power …

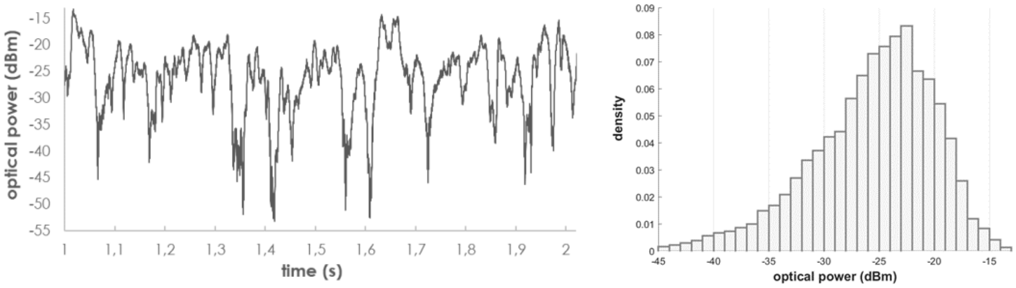


Figure 9. Example of received optical power measurement in outdoor transmission experiments

Depending on the conditions, the optical budget link between the HPOA output and the LNOA input was between 49 and 57 dB. Although the received optical power was relatively high (up to -22 dBm), fadings were deep (up to -20 dB) and frequent, affecting digital and analog performances.

For OOK & DPSK, BER was averaged along 1 second. For one optical channel, BER was varying around 9.10^{-5} to 2.10^{-4} and from 2 to 9. 10^{-4}, for 25G OOK and DPSK modulations respectively. For DPSK, BER is higher than expected and this could be explained by a non-optimized setting at the receiver in the field.

WDM transmissions were achieved on adjacent optical channels carrying DPSK, OOK but also coherent signals at high symbol rate provided by ETH. Transmissions up to four adjacent channels were performed with the same modulation format, thus resulting in a 100 Gbps link without any FEC. For fair comparison, signals that were transmitted almost in the same time were compared as evolution in weather conditions lead to an the evolution of performances. No crosstalk was observed. Fr instance, for 25G OOK, a BER of 1.10^{-4} was obtained with one channel and 8.10^{-5} was achieved with two channels. Similar behavior was observed for DPSK. This slight improvement can be explained by better weather conditions.

By multiplexing OOK & DPSK channels, it was possible to compare their performance under the same turbulence conditions. Although DPSK presented a slightly higher BER, it looks like this modulation format was more robust than OOK. Synchronization loss occurred less often and BER was more constant. Up to 98 synchronization loss were counted for OOK during 137 seconds and none for DPSK under the same duration and conditions. Plus, the histograms in Fig. 10 below shows BER dispersion for OOK and DPSK signals for the same transmission. DPSK BER was found to be less sensitive to turbulences than OOK.

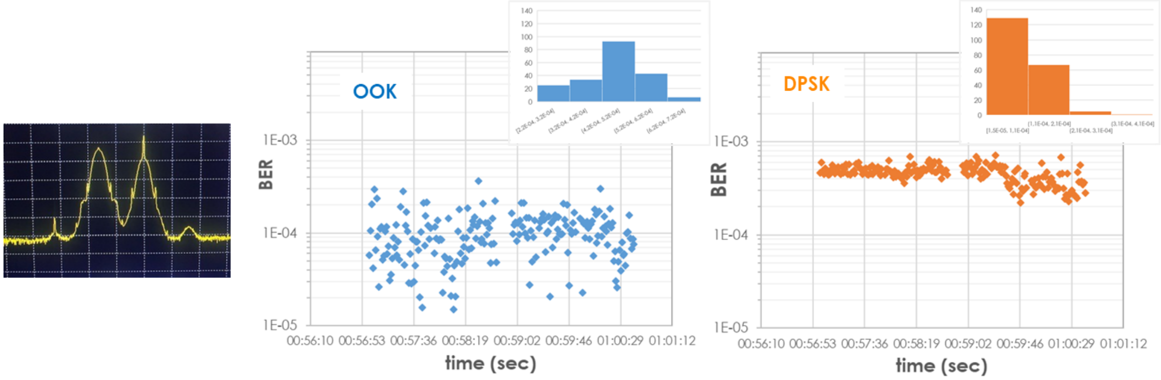


Figure 10. BER over time for 25G OOK & DPSK multiplexed on adjacent channels

RF analog modulation was performed for QPSK, 8-PSK, 16-APSK and 16 QAM, at low symbol rate (10 MSps) in order to record long sequences. Constellations acquisition is an averaging over a duration of the order of 1 ms. It was possible to observe the high dynamics of an analog transmission with EVM variations from 2% up to 40% within the same second. Low EVM was even measured with only tip/tilt correction. Fig. 11 below represents EVM histograms for 8-APSK, 16-APSK, 16-QAM modulations recorded along 30 seconds and with similar turbulences.

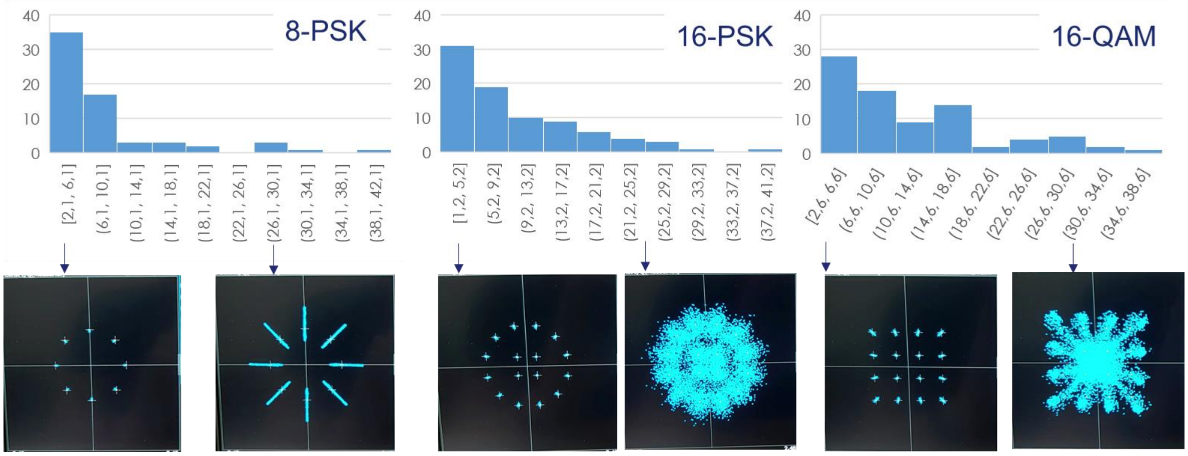


Figure 11. 8-PSK, 16-APSK and 16-QAM EVM across the outdoor free space optical link

5. CONCLUSION

System evaluation in the laboratory of transmit and receive optical communication breadboard models developed within the H2020 VERTIGO project have been reported together with the first results of an outdoor demonstration of FSO communications over a long distance, supposed to be representative of GEO-to-ground link.

Laboratory transmission experiments with an amplitude free space propagation channel emulator allowed for first assessment of modulation formats and rates, and comparison of their respective performance. 10G data-rates were found to be more affected by turbulences than 25G data-rates. OOK & DPSK showed similar power penalties for both uplink and downlink directions. For 25G OOK & DPSK downlinks, very low (~1dB) power penalties were measured.

For RF analog modulation, the EVM was also affected by the turbulences and quite similar degradation was observed for the five modulations (QPSK, 8-PSK, 16-PSK, 16-QAM, 32-QAM) tested. The BER was then estimated from these EVM measurements. Very low BER ($<10^{-10}$) were achieved for both directions. As expected, for a given estimated BER, 16-QAM suffers a larger power penalty than QPSK.

The outdoor FSO transmission trial was performed along a very demanding Line of Sight with deep, frequent and fast fadings. OOK 10 & 25G and DPSK 25G signals were successfully transmitted, with up to 4 WDM channels resulting in a total throughput of 100 Gbps. Raw BER before FEC around 10^{-4} and down to 10^{-6} were reached during several minutes. RF analog signals with DVB-S2 like signals were also successful with low EVM (2-3%).

In this paper, we focused on OOK, DPSK and RF modulations using optically pre-amplified direct/differential detection with prior adaptive optics, but other approaches were evaluated during this outdoor demonstration. .In particular, ETHZ achieved throughput records using coherent modulation [16]. Additional results are expected to be obtained by further correlating the transmission and communication performance together with the measured atmospheric conditions such as the Fried parameter or the scintillation index.

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