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Assessment of the effective performance of DPSK vs. OOK in satellite-based optical communications

A. Maho[a], M. Faugeron[a], A. Le Kernec[a], K. Elayoubi[b], M. Sotom[a]
[a] Thales Alenia Space, 26 av. J.-F. Champollion, Toulouse, France
[b]IRT S[t] Exupéry, 3 rue Tarfaya, Toulouse, France
anaelle.maho@thalesaleniaspace.com

ABSTRACT

This paper reports on the assessment of the communication performance of DPSK- and OOK-based free-space optical (FSO) links in satellite-based applications, including LEO downlinks, LEO inter-satellite links, and feeder links for GEO Satellites. The performance is assessed by means of simulations as well as transmission experiments at 10 Gbps. The impact of optical filter bandwidth, optical delay-line-interferometer accuracy, frequency offset between transmitter laser and receiver, is quantified. OOK performance critically depends on transmitter extinction ratio, and proves robust to Doppler-induced frequency offsets. DPSK is sensitive to any laser wavelength drift and offset with the DLI response. Nevertheless, compensation of this drift is considered manageable, making it possible to maintain the 3dB advantage of DPSK vs. OOK in practical use conditions.

Keywords: Free Space Optical (FSO) communications, OOK, DPSK, Optical Inter-Satellite Link (OISL), optical feeder link

1. INTRODUCTION

With their potential for much higher capacity, smaller beam divergence, and lower terminal mass, volume and power, free-space optical (FSO) communication links are anticipated to dramatically exceed the performance of traditional radio-frequency-based solutions in an increasing number of satellite-based applications. In-orbit demonstrations so far were based either on simple On-Off Keying (OOK) with direct detection, or on Binary Phase-Shift Keying (BPSK) with complex homodyne detection[1]. Differential Phase-Shift Keying (DPSK) is compatible with optical demodulation and direct detection, thus offering the advantage of about 3dB higher noise tolerance at affordable added complexity[2]. Even though it has been considered for a long time[3], only a few forthcoming FSO link demonstrations in space, namely LCRD[4] and JDRS[5], will operate DPSK, and its effective suitability for other space applications is still under assessment. The present paper aims at evaluating the impact of critical parameters on DPSK transmission performance in satellite-based FSO communications, with a special attention paid to direct-to-the-Earth LEO down-links, inter-satellite links (ISL) in LEO constellations, and feeder links to high-throughput GEO satellites. The specific requirements deriving from the Doppler effect are taken into account. The theoretical performance of 10 Gbps DPSK- and OOK-based optical communication links, established by means of a commercial simulation software tool, are reported with Non-Return-to-Zero (NRZ) coding. Then, NRZ DPSK and OOK transmission experiments at 10 Gbps channel rate are reported and the results are compared. An experimental assessment of the critical link elements has been carried out and their influence on the Bit Error Rate (BER) performance has been quantified. Such parameters include optical filter bandwidth, optical delay-line-interferometer accuracy, frequency offset between transmitter laser and receiver.

2. SATELLITE-BASED FSO COMMUNICATION APPLICATIONS

FSO communications hold the potential to offer unrivalled advantages over RF counterparts, mostly stemming from the large difference in wavelength. Moving to higher carrier frequencies increases the intrinsic capacity of a communication system. At 1.55 µm wavelength, the carrier frequency is about 190 THz and a few THz at least are available within the so-called C-band. As the optical wavelength is small, FSO beams feature very high directivity with a divergence much smaller than for RF beams; any kind of interference or interception is therefore very unlikely. Whereas RF systems require spectrum licensing by regulatory authorities in order to avoid congestion and interference, FSO solutions are free from any frequency regulation. Lastly, at equivalent capacity, FSO communication systems come up with terminals of smaller size and lower mass than RF antennas. For all the above reasons, FSO communications have raised an increasing interest from space operators and system providers for various applications.

Optical links are envisioned to downlink to the ground, large amounts of data generated on board LEO-orbiting satellites, for instance by Earth Observation instruments. There is a will to increase the instantaneous data rate beyond the few Gbps' achievable in X/Ka bands so as to enhance the aggregate volume of daily transmitted data. The consultative committee for space data systems (CCSDS) has issued preliminary recommendations for FSO communications. OOK and DPSK modulation formats are recommended options respectively for low-complexity and high-data rate system solutions. Thales Alenia Space has developed the OPTEL-μ® terminal[6], that enables to transmit data from LEO satellites to an optical ground station (OGS) at 2 Gbps rate with OOK coding, and with only 8 kg mass, 8 liters volume and 45 W power consumption, has very low impact on the spacecraft resource. OOK was selected as the optimal option for lowering complexity and ground station maintenance needs. Later, it could be configured to operate also as a DPSK transmitter, which will call for higher complexity at the ground station. The design of any FSO communication system requires to establish a link budget accounting for all impairing effects. In case of a LEO down-link, the free-space losses are varying all along the orbit so that ways of adapting rate w.r.t. losses have been proposed, e.g. by using variable coding rate, burst mode or wavelength-division multiplexing (WDM).

Innovative constellation concepts and initiatives have been proposed for telecom applications in the last years, with the goal to offer worldwide coverage and low-latency communications services. LEO constellations featuring 100+ satellites are intended to support mesh connectivity at capacities ranging from Gbps to 100 Gbps. Optical inter-satellite link (OISL) is considered as an enabling technology of these constellations. Optical link solutions based on 1.5 µm are preferred because of the general availability of the technology on ground, but also because WDM capabilities open attractive perspectives in terms of modularity, adaptive rate, redundancy, all-optical routing … Mass, size and power budgets are constrained for accommodation on small-to-medium platforms. Cost and manufacturability are major design drivers as 100's of terminals have to be delivered in short lead times. Constellations are based on polar orbital planes with inter-satellite links within the same plane and between neighboring planes. Thus, 4 terminals are typically required to support two intra-plane, inter-satellite links to the ahead and rear satellites, and two inter-plane links to the next satellites on the right-hand and left-hand neighboring planes. Channel rates in the 10^{+}Gbps range are typically anticipated. OOK is the option for minimal complexity, DPSK can be an option to release the link budget, either for increasing the data rate or reducing the power consumption, at the expense of additional complexity.

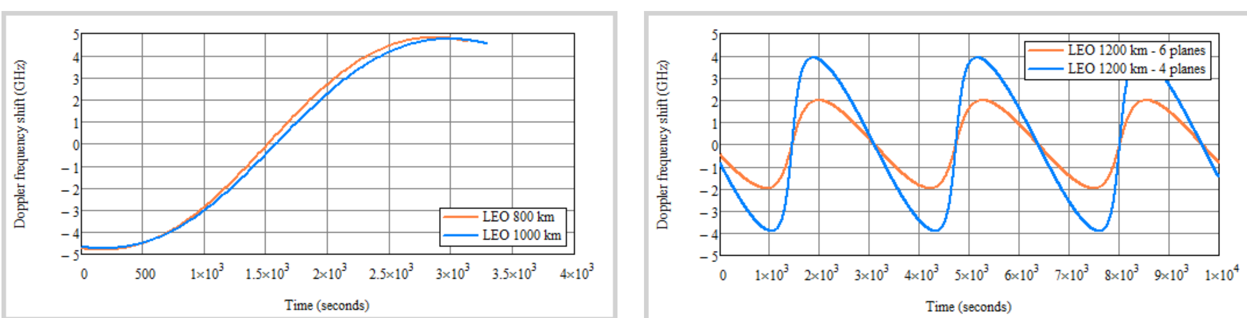

Figure 1. Optical carrier frequency shift through Doppler effect in typical LEO-ground (left) and inter-plane, LEO constellation inter-satellite (right) FSO links

In both LEO downlinks and inter-plane inter-satellite links, the distance and relative position of the communicating terminals are continuously varying along the orbit. As a consequence, optical terminals have to cope with Doppler shift, possibly calling for active compensation. Figure 1 shows the variations vs. time of the optical carrier frequency due to Doppler effect, for typical LEO-ground optical down-links (left), and inter-plane, LEO constellation optical inter-satellite links (right). The maximum frequency shift depends on the system configuration and orbit but is typically in the range of ±4 GHz, which is about ±20 ppm. The bit rate incurs same relative variations, that represent about ±0.2 Mbps at 10Gbps.

Recent years have also seen the development of very-high-throughput satellites (VHTS) intended to offer very high-speed Internet access to millions of users over vast coverage. Throughputs in the 100's Gbps range are targeted and are expected to exceed 1 Tbps in future generations. The use of Q/V frequency bands beyond the Ka-band, addresses this challenge. A number of ground gateways, that increases linearly with the throughput is required to support the aggregated system capacity. Terabit-class VHTS call for new solutions: optical feeder links (OFL) may provide the alternative to the RF feeder station networks, making it possible to feed a VHTS from one optical ground station at a time, provided that a geographical diversity network of ten-to-twelve stations is implemented to reach an acceptable availability. Current approaches focus on optical comm. architectures at 1.5 µm, HD-WDM over C (possibly L) bands. Line rates well above 10 and up to 50 Gbps are considered in order to restrict the number of optical channels. Communication architectures and waveforms achieving high power and spectral efficiencies are required also because of power efficiency and high power management constraints placed at GEO and ground terminals; 25 Gbps DPSK and 50 Gbps DQPSK are among possible options.

3. OOK/DPSK OPTICAL COMMUNICATION LINK SIMULATIONS

Optical link models have been used to predict the communication performance[7]. The OOK transmitter was made up of a CW DFB laser and a Mach-Zehnder intensity modulator, and the receiver included a pre-amplification stage based on a low-noise Erbium Doped Fiber Amplifier (EDFA). Transmitted data stream was typically a pseudo-random binary sequence (PRBS) of 2^{31}-1 length. The electrical NRZ OOK signal had a raised-cosine shape with a raise/fall time of 22 ps. In case of DPSK modulation, a differential encoder generated the DPSK waveform from the PRBS sequence. The phase reference was then provided by the signal itself. Both OOK and DPSK receiver chains contained an optical pre-amplifier with 5 dB noise figure, an optical band-pass filter, detectors with 0.9 A/W responsivity, and included an electrical filter of 5^{th} order Bessel type. The DPSK receiver chain contained an optical delay line interferometer (DLI) to decode phase modulation and a balanced dual-detector receiver.

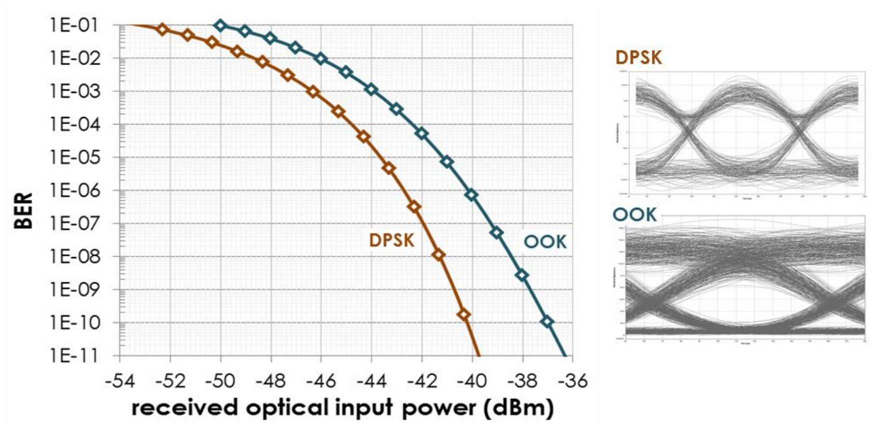

Figure 2. Simulated BER performance (left) and 10^{-9} BER eye-diagrams (right) for 10 Gbps NRZ-OOK and NRZ-DPSK

In such communication links, the Bit Error Rate (BER) performance relies on parameters[8] dependent on each other. For better understanding their respective influence, a simulation tool was implemented based on a commercial software. Figure 2 gives simulated BER curves, i.e. BER variations vs. the optical power at the receiver input. NRZ OOK performance was optimized by increasing the extinction ratio (ER). At the end, NRZ DPSK performance offers a power advantage of 3 dB at 10^{-9} and 2.4 dB at 10^{-4}, both with respect to NRZ OOK.

	OOK		**DPSK**	
	BER=10^{-9}	**BER=10^{-4}**	**BER=10^{-9}**	**BER=10^{-4}**
Optimal optical 3dB-bandwidth	50 GHz	20 GHz	20 GHz	20 GHz
Power penalty	0.14 dB for 20 GHz BW	3 dB for 10 GHz BW		2 dB for 10 GHz BW
		0.5 dB for 50 GHz BW	0,2 dB for 50 GHz BW	0 dB for 50 GHz BW

Table 1. Influence of the 3 dB-bandwidth (BW) filter on the power penalties at 10^{-4} and 10^{-9} for NRZ OOK and DPSK signals.

As already reported [8,10], the optimum optical filter bandwidth results from a trade-off between noise filtering and inter-symbol interference (ISI) which can close the eye and raise the 0-level. Table 1 shows the BER performance obtained by simulations, for optical filter bandwidths varying from 10 to 100 GHz. As expected, the power penalty increases with the bandwidth because of the increase of amplified spontaneous emission. Inversely, choosing a filter of the order of the modulation bandwidth increases the penalty by truncating the information carried in the signal.

4. EXPERIMENTAL ASSESSMENT OF COMMUNICATION PERFORMANCE

In parallel, a FSO communication link test-bed was developed so as to experimentally assess various configurations and formats. The typical set-up is shown in Figure 3 below, with two channels for OOK and DPSK modulation.

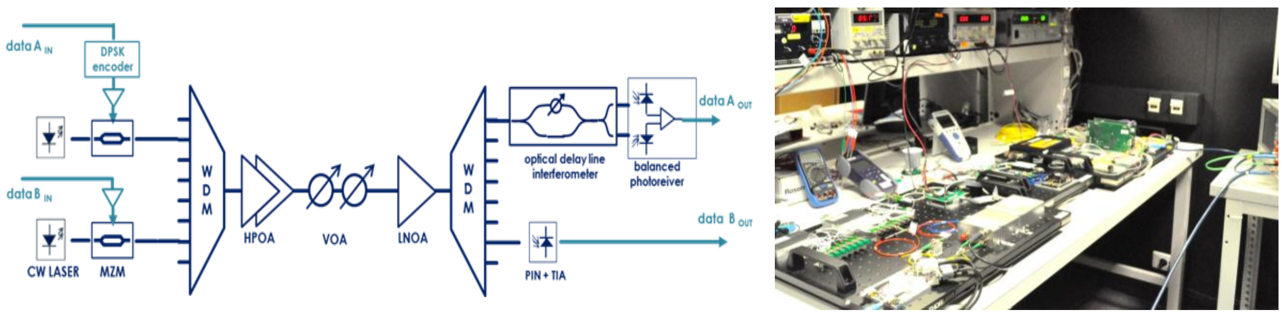

Figure 3. FSO communication link test-bed: (top) schematic with 2 OOK/DPSK channels, (bottom) picture of the set-up

Continuous-wave DFB lasers emitting at 192.9 and 192.8 THz respectively were used with +17 dBm output power. Modulation was achieved by Lithium Niobate Mach-Zehnder modulators (MZM) with an electro-optical bandwidth of 12 GHz. The maximum extinction ratio was 14.2 dB for NRZ OOK signal. For DPSK, an electrical coder was inserted after the pattern generator. For both OOK and DPSK, a RF amplifier was added before the MZM to increase the modulation signal amplitude. Optical channels were then multiplexed through a flat-top, 100-GHz-spacing wavelength multiplexer and input to an EDFA delivering +35 dBm output power. The receiver chain was made of a low-noise optical amplifier with 4.5 dB noise figure, and a tunable optical filter emulating the wavelength demultiplexer. When operating OOK, the signal was transmitted to a PIN-TIA receiver with 12 GHz E/O bandwidth, and 0.8 A/W DC responsivity. When operating DPSK, the signal was first input to an optical tunable delay line interferometer and then to a balanced dual-detector receiver with E/O bandwidth of about 13 GHz and responsivity of 0.8 A/W. The 10 Gbps signal was a 2^{31}-1 PRBS. No electrical filter was inserted before the error detector.

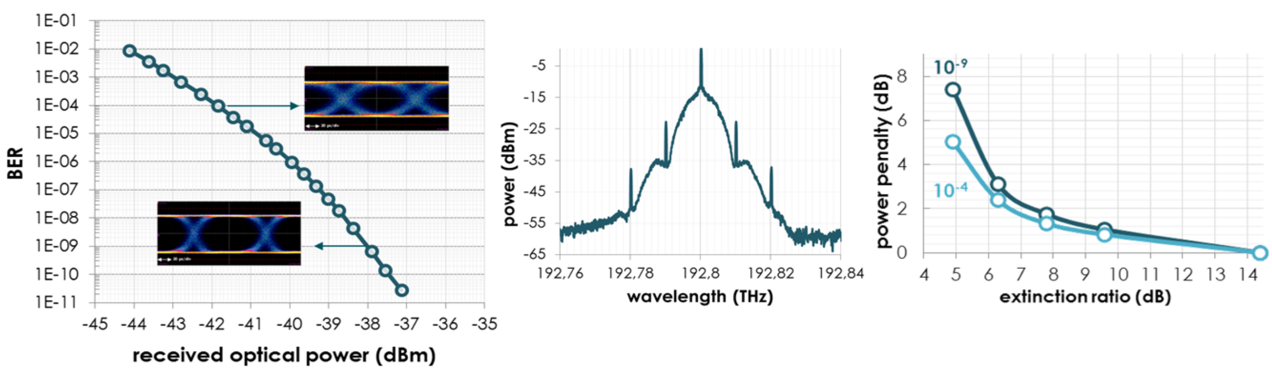

Figure 4. BER curve for a 10 Gbps NRZ OOK (left) with eye diagrams at 10^{-4} and 10^{-9} (inset), optical spectrum at Tx output (middle) and influence of the extinction ratio at 10^{-4} and 10^{-9}.

Figure 4 shows the results obtained in NRZ OOK. A detection sensitivity of -38 dBm at 10^{-9} was obtained, which matches well with the simulations. The 5 dB power penalty with respect to the theoretical limit, can be explained by the use of a non-ideal pre-amplified receiver. Also, Figure 4 (right) shows how a finite ER induces a power penalty, that grows rapidly well above 1 dB when the ER gets lower than 10dB. These results are consistent with the model developed by Winzer[8].

Figure 5 shows the results obtained in NRZ DPSK. Typical spectrum at each port of the DLI is shown. They are complementary of each other and well centered around the channel wavelength. Sensitivities of -39.8 dBm at 10^{-9} and -43.4 dBm at 10^{-4}, are obtained, which is 0.9 and 1.4 dB respectively higher than the simulations, and 6.1 dB higher than the theoretical limit at 10^{-9}.

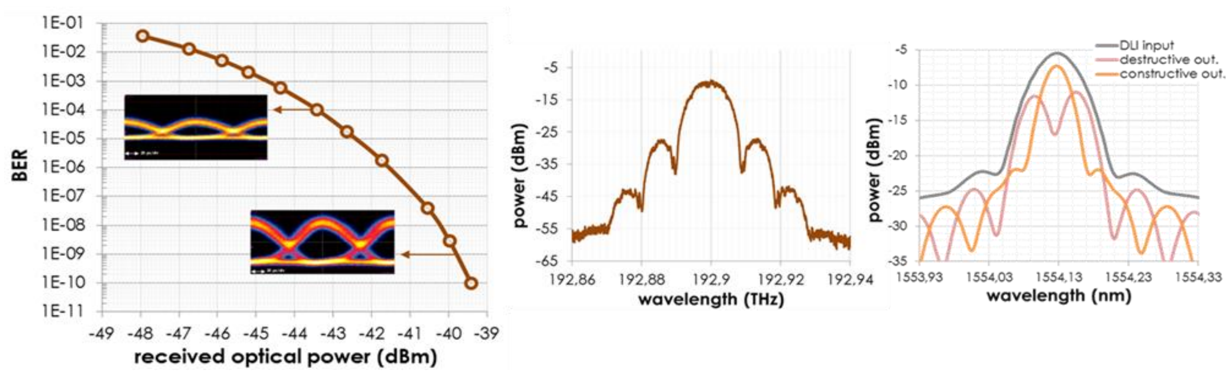

Figure 5. BER for a 10 Gbps NRZ DPSK signal (left), eye diagrams at 10^{-4} and 10^{-9} (inset), optical spectrum at Tx output (center) and optical spectra at each output of the delay line interferometer (right).

As mentioned above, optical channel filtering is key for performance optimization. In both DPSK and OOK, power penalties were found to be lower with a Gaussian filter than with a flat-top filter. As seen with simulations, the power penalty increases rapidly below the optimum bandwidth and increases softly above.

For an ideal preamplifier receiver, the theoretical optimum full-width, 3dB bandwidth was found to be about twice the data rate[8]. An optimum of 30-50 GHz (i.e. 3-5 times the data rate) was experimentally observed, which can be explained by a non-rectangular pulse shape and a finite extinction ratio[8]. Concerning the DPSK signal, the optimum full-width, 3dB bandwidth was found to be around 30-40 GHz, at both 10^{-4} and 10^{-9} BER.

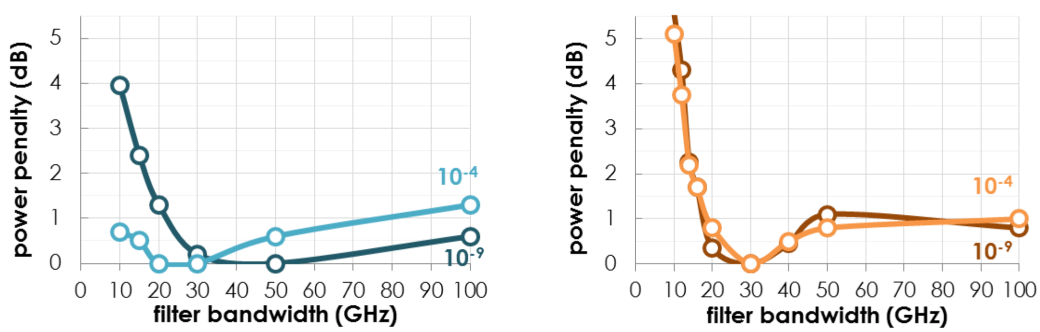

Figure 6. Influence of optical filter bandwidth on detection sensitivity for 10 Gbps NRZ OOK (left) and NRZ DPSK (right)

Doppler shift tolerance was assessed by measuring the variations of the BER curve against a laser wavelength drift. Based on the estimations of paragraph 2, a wavelength drift of +/- 5GHz was considered and emulated by finely tuning the laser wavelength. In practice, the laser wavelength drifts during its propagation but the wavelength multiplexer is wide enough to have negligible influence on the drifted signal.

NRZ OOK was found to be very robust to wavelength drift as shown in Figure 7 (left). On the contrary, NRZ DPSK performance is more sensitive to any wavelength drift. The frequency offset between the laser and the DLI response has to be kept within $\pm$0.5 GHz approximately, for the penalty to be lower than 0.5 dB. Theoretically, Figure 7 should be symmetrical. The observed asymmetry is explained by a non-perfectly centered reference signal and also by a mismatch between the two photodiodes of the balanced-dual-detector receiver. This can be understood by looking at the output spectra of the DLI where interferences are neither constructive nor destructive. +/- 5 GHz offsets correspond to half of the FSR. Constructive and destructive ports are inversed compared to the reference configuration but it should not impair the detection sensitivity.

Another consequence of the Doppler effect is the data bit rate variation. For OOK modulation, this variation is considered not to impair the performance. For DPSK modulation, there is mismatch between the actual channel rate and the Free Spectral Range (FSR) of the DLI fixed at 10 GHz. The data rate was changed experimentally by tuning directly the clock at the transmitter side. The measured penalty was less than 0.5 dB in the 9.8–10.2 Gbps range, which is 1000 wider than the maximum bit rate wander induced by Doppler effect.

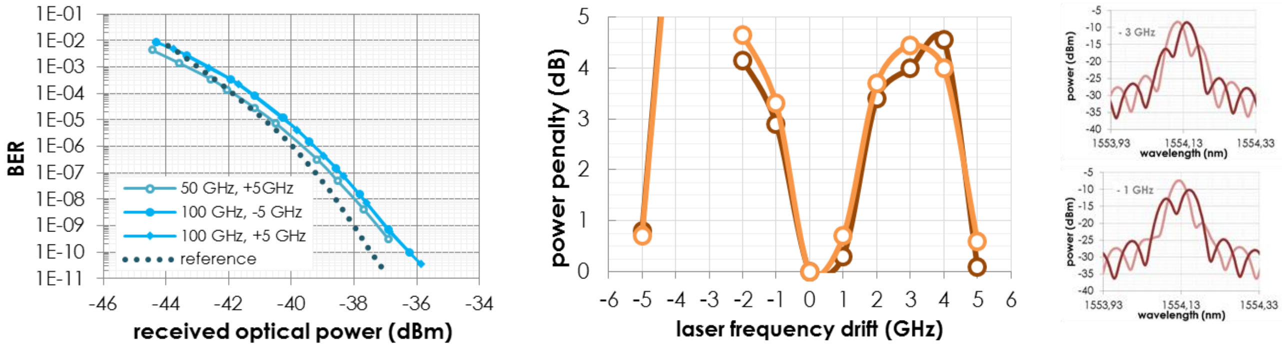

Figure 7. (left) BER at 10 Gbps OOK for wavelength drift of +/- 5 GHz for filters of 50 and 100 GHz bandwidth, (center) power penalty vs. wavelength drift for 10 Gbps DPSK, (right) output spectra (constructive and destructive ports) for -3 and -1 GHz offsets.

5. CONCLUSIONS

The actual performance of DPSK vs. OOK optical communication links has been assessed by means of simulations as well as transmission experiments in a dedicated test-bed, emulating use cases including LEO down-links, LEO inter-satellite links, and feeder links to GEO satellites. NRZ DPSK and OOK experiments at 10 Gbps channel rate have been carried out, and results compared to the expected BER and detection sensitivity performance.

The impact of optical filter bandwidth, optical DLI accuracy, and frequency offset between transmitter laser and receiver, has been quantified. OOK was confirmed to critically depend on transmitter extinction ratio, and to keep robust to Doppler-induced frequency offsets. On the contrary, DPSK was shown to be sensitive to any center wavelength drift and offset with the DLI response. However, it seems feasible, at the expense of additional complexity, to compensate for this drift so as to achieve the ultimate DPSK performance and maintain the 3dB advantage of DPSK vs. OOK in practical use conditions.

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