Phase locking of an Optical Injection Phase-lock Loop coherent receiver under emulated atmospheric fading conditions

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Abstract: An Optical Injection Phase-Lock Loop coherent receiver has been tested against various levels of deep atmospheric fading to experimentally evaluate its feasibility in a ground-to-satellite optical communications application.

1. Introduction

The demand for capacity on data communication satellite networks is growing; in the radio-frequency (RF) domain, some of the limitations are the narrow bandwidth available to the service providers, the cost of regulated spectrum, and the size, weight and CAPEX of the communication terminals. An alternative to RF is to transmit in the optical domain, therefore taking advantage of the increased unlicensed spectrum and security [1]. The current technologies for satellite optical communications tend to implement the links using components from the mature terrestrial long-haul fibre optic infrastructure, adapting them to the specific satellite use cases.

One of the elements that differs between satellite links and the fibre optic environments is the concern about power consumption. In a terrestrial link, the power consumed by the transceiver is not as important as the throughput; on the other hand, in a satellite ecosystem, the power available for the space segment is restricted.

To provide greater spectral efficiency when transmitting data, coherent detection is being investigated for satellite links. With coherent detection, as opposed to direct detection, data can be coded both in amplitude and phase of the signal, and recovered by mixing the incoming waveform with a local oscillator (LO). The detected electrical signal is digitised, and recovered with a digital signal processing (DSP) approach in a terrestrial link [2]. It has been shown that the DSP block in a coherent receiver for terrestrial links is one of the most power hungry elements [3]. Therefore, an analogue approach may be preferable, if it consumes less power. As discussed in [4], an option could be to use an Optical Injection Phase-lock Loop (OIPLL) to compensate for phase and frequency detuning between the transmitter and the receiver [5].

To further prove the use of such a system in a ground-to-satellite environment, the locking characteristics against the deep and short power losses the optical signal encounters while travelling through the atmosphere need to be characterised. These can span from 3 dB to 10 dB, with fade lengths from hundreds of nanoseconds to tens of milliseconds [6]. In this paper it will be demonstrated that the OIPLL would be able to cope with such power drops, maintaining lock when the signal returns.

2. The OIPLL

The OIPLL allows the recovery of frequency and phase of the transmitted signal without any need for DSP. The OIPLL consists of 1) optical injection locking (OIL), which is very efficient at correcting phase changes between the incoming signal and LO laser, and 2) a PLL which controls the bias current of the LO allowing to significantly extend the locking range of the OIPLL receiver.

The schematic diagram of the OIPLL used in these experiments is shown at the bottom right of Figure 1. In the current implementation, the OIPLL is built with pigtailed components; therefore, to maintain phase coherence between the two arms of the receiver hybrid over long periods, a piezo stretcher is included. This, in combination with a lock-in amplifier, allows the two arms to be maintained at the same length, giving overall stability.

The OIPLL may be a good candidate to reduce the power consumption of a coherent satellite receiver, given its compensation of fast and varying frequency shifts (such as Doppler) [7] and, as it will be discussed in this paper, its resilience to atmospheric fading.

3. Fading Characteristics

An optical beam travelling through the atmosphere is subject to fast fading of various magnitude and duration. For the purposes of this demonstration, the characterisation and statistical modelling discussed in [6] will be used to stress test the OIPLL.

Depending on the strength of the atmospheric turbulence, multiple fading vectors can be derived. The eight turbulence levels presented in [6] have been generated and used to test the OIPLL. These cases are summarised in Table 1, where the number of fades represents the count of fades over 100 s patterns.

Table 1. Attenuation Statistics [6]

Fade Length /ms	Number of fades /100s	Fade Length /ms	Number of fades /100s
(3dB/6dB/10dB)		(3dB/6dB/10dB)	
0.81 / 0.46 / 0	2187 / 3 (150) / 0	2.1 / 1.9 / 2.1	4374 / 534 / 34 (150)
1.36 / 0.79 / 0.38	13458 / 2168 / 17 (150)	1.78 / 1.28 / 1.13	12734 / 3509 / 272
2.43 / 1.7 / 0	787 / 1 (150) / 0	5.45 / 4.37 / 3.5	1691 / 230 / 16 (150)
3.9 / 2.3 / 1.7	4623 / 789 / 4 (150)	4.87 / 3.5 / 2.7	4857 / 1240 / 115

Each of the rows represents an atmospheric characteristic defined by an increasing scintillation index and jitter level. As shown, the first row represents an atmosphere dominated by short 3-dB fades, whereas the last case at the bottom right of the table comprises long fades at all depths at high occurrence frequency. The values in brackets represent the actual fading number used for the experimental procedure, as will be discussed in the next section.

4. Methodology and Experimental setup

In order to test the OIPLL against the above fading conditions, a high-speed variable attenuator (Agiltron NPOA) has been used. This is driven by electrical signals generated by an arbitrary waveform generator (AWG), translating the fading waveform into an attenuation of the optical signal. The OSNR was set by changing the gain on two daisy-chained Erbium Doped Fibre Amplifiers (EDFAs) connected to the system through a 50/50 coupler. From the coupler, the input OSNR to the OIPLL could be monitored through an optical spectrum analyser (OSA). The experimental setup can be seen in Figure 1.

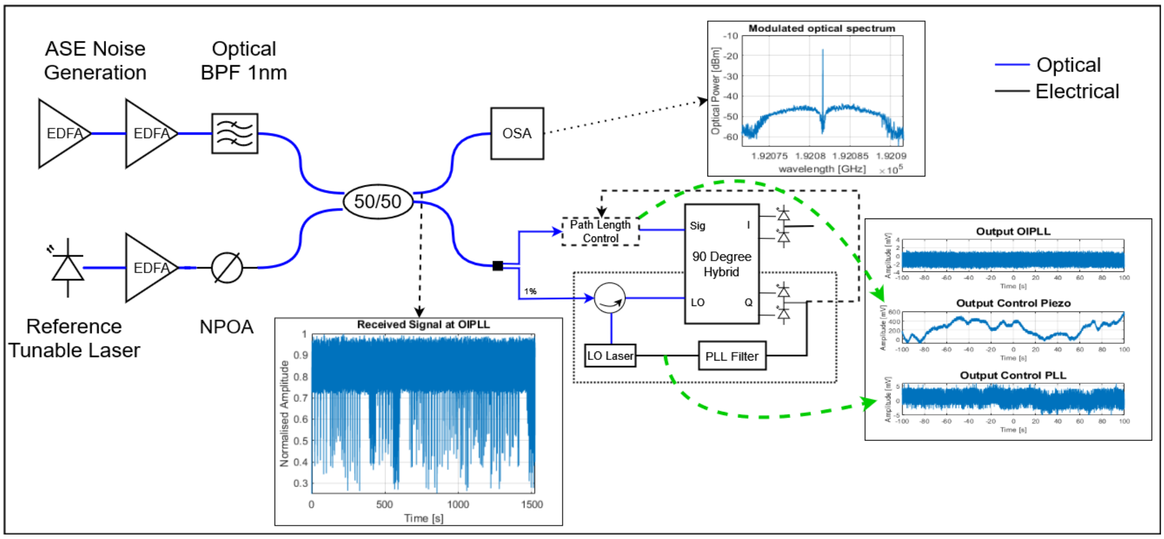

Fig. 1. Experimental Setup.

The attenuation patterns presented in [6], and discussed in section 3, were tested under multiple conditions. The optical signal-to-noise ratio (OSNR) at the input of the OIPLL was varied by changing the gain of the daisy chained EDFAs to provide values between 25 dB and 14 dB. The OSNR was measured from an optical spectrum analyser over a 0.1 nm bandwidth and at 0.5 nm distance from the peak of the received signal. The injected signal power was adjusted using a variable attenuator in the range from -27 dBm to -36 dBm. The LO power was 3 dBm throughout the experiment. Therefore, the injection ratio was varied from -30 dB to -39 dB. The lower limit for the OSNR under test was chosen based on the findings in [7].

In order to evaluate the stability of the OIPLL, the attenuation patterns were repeated for 100 seconds. If the locking was maintained, then the pattern was deemed successful. In the bottom inset of Figure 1 the received signal in time is shown for a duration of approximately 25 minutes. This is a sample of the received pattern to the OIPLL for illustration purposes normalised in linear scale at an OSNR of 14 dB.

Each fade depth was tested individually, giving 24 scenarios per OSNR. If a fade depth appeared less than 100 times over the 100 seconds, its presence was increased, generating a worst case than the statistical one, allowing for such a scenario to be tested. The number of occurrences of those fades is shown in brackets in Table 1.

Additionally, some 10 Gbit/s BPSK 8b10b coded signal was modulated onto the transmit signal to demonstrate that locking was still stable under fading conditions with data being transmitted. This was not present on all measurements, but only when the OSNR was set at 14 dB (worst case). A sample of the received spectrum is shown in Figure 1. It can be seen that since the transmitted waveform is 8b10b coded its close-to-carrier frequency component has been reduced, which improves the performance of the OIPLL [8]. Nevertheless, the modulation signal deviation was less than Vpi, therefore a carrier component is present and used as reference for the OIPLL.

The inset at the bottom right of Figure 1 shows some typical feedback signals from the control electronics of the PLL and the piezostretcher together with the output signal at an injected power of -50 dBm at an OSNR of 12 dB; this was to test the locking limit of the OIPLL. The output of the OIPLL can be seen to be constant, as expected. The noise at the output of the OIPLL when locked is coming from ASE noise.

The OIPLL was also tested in these conditions against 10 dB fading for 300 ms. Although locking was lost, as expected, the OIPLL reacquired locking when the signal returned.

5. Discussion

The OIPLL was able to maintain lock over all the generated vectors from an OSNR of 25 dB down to 14 dB, and at all injection ratios investigated, hence from -30 dB to -39 dB. This demonstrates that the OIPLL based receiver remains operational despite the link budget conditions being changed by up to 10 dB due to the atmospheric fading. The testing on the OIPLL demonstrated stable locking at injection ratios as low as -53 dB (-50 dBm injected power). For smaller injection levels, the OIPLL's locking bandwidth was too small to cope with the weak received signal. This is consistent with the locking under fading conditions observed above, as even deep (10 dB) fades at -40 dB injection ratio would result in an injected power that still would allow stable locking to be achieved. The stability of the system could be further improved by integrating the OIPLL in a photonic integrated circuit (PIC), removing the need for the piezostretcher.

6. Conclusion

The OIPLL has already been shown to be able to operate at high data rates and with no dependency on the baud rate in its architecture [5], therefore providing flexibility in the receiver architecture.

In this paper it has been tested experimentally how the OIPLL would react to both strong (10 dB) and weak (3 dB) signal fades, of different duration. It has been shown that the subsystem successfully coped with the statistical atmospheric fading proposed by [6]. At a lower injection ratio of -53 dB, locking was lost during fades, but the OIPLL was able to reacquire lock when the signal level increased at the end of the fade.

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