Optical Signal Tracking for Robust PAM4 Deployment in Filterless Metro Network Scenarios

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Abstract: Highly accurate and reliable optical signal tracking is proposed that estimates sub-GHz laser drift failures by analyzing spectra acquired by cost-effective coarse-granular OSAs. Its application on PAM4 systems in filterless metro networks brings added robustness.

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1. Introduction

Filterless optical networks (FON) represent an attractive solution for metro networks due to CAPEX savings and simple control and maintenance operations. The lack of intermediate filtering nodes converts FON in a kind of *gridless* network since the strict channel spacing of the spectrum switched optical networks (SSON) is relaxed. However, in contrast to SSON where the signals are dropped at their destination, they continue to spread over the transmission line in FON, which leads to spectrum waste and efficiency penalties.

The inherent *gridless* potential of FON could allow the channels to be placed very close to each other aiming to alleviate spectrum waste. Nonetheless, as highlighted in [1], the bottleneck is that (un)intentional laser drift (LD) of a transponder (Tp), possibly due to failure or its misconfiguration, might lead to overlapping of neighboring channels. In addition to the overlapping issue, LD could have a detrimental impact on the lightpath itself due to detuning w.r.t. the receiver optical filter. However, while coherent detection receivers can easily track the central frequency (CF) of the transmitted signal by evaluating the offset with local oscillator, direct-detection (DD) systems detect only the intensity of the optical signal and can hardly estimate the LD. Note that DD systems, e.g., pulse amplitude modulation (PAM), have recently attracted attention for metro applications due to cost savings with respect to coherent solutions. Therefore, it is of paramount importance to devise robust and reliable monitoring solutions to track optical signals that allow FON to exploit novel transmission solutions based on PAM format while go into operation with lower margins.

In this regard, optical spectrum monitoring, with the help of cost-effective coarse-resolution Optical Spectrum Analyzers (OSA) [2], has been proposed as a novel solution to monitor the proper operation of lightpaths in optical networks [3]. This approach has been demonstrated to identify and detect several soft-failures, including LD, filter-shift and filter tightening. Authors in [1] proposed a real-time spectrum surveillance solution to track the CF of the active lightpaths in FON; the solution monitors every lightpath *individually* and was based on extracting features from the optical spectrum, which makes the solution *dependent on the resolution of the OSA.*

In this work, we propose an accurate CF estimation procedure that relaxes the dependency on the OSA's resolution. In addition to its excellent *individual* lightpath CF tracking, it is enriched with the capability of using tracking information from one signal to enhance the tracking accuracy of neighboring signals (we call this *contextual*). We evaluate the performance of the proposed procedure in a FON with PAM4 transmission systems. We ultimately demonstrate that the proposed procedure is capable of detecting LD in order of 100s of MHz with excellent accuracy using optical spectra acquired by an OSA with 1.8 GHz resolution.

2. Motivation of optical signal tracking in FON

An example of FON connecting packet nodes is presented in Fig. 1. FON nodes comprise of only passive optical splitters and combiners and therefore, they are exploited to create simple network topologies like buses or horseshoes. However, FONs can be combined with OXCs (as suggested in Fig. 1) and participate in extending mesh networks based on SSON. In FONs, traffic is broadcasted throughout the network; for instance, in Fig. 1 four lightpaths are created: R1->R4 (labeled 1), R2->R3 (2), R2->R5 (3), and R3->R5 (4). Let us imagine that Tps for lightpaths 2 in R2 and 4 in R3 experience a LD failure drifting the signals to the right in the spectrum. In this case, signal 3 might be affected as the spectrum of signal 2 overlaps it, whereas signals 2 and 4 can be affected as the receiver could not be able of tracking their CF and misalignment between signal and the optical filter at the receiver might occur. One conservative solution could be assigning large channel spacing thus deteriorating even more the spectral efficiency of FON. A more effective solution is to consider a reliable and robust optical tracking procedure to detect LDs accurately, so Tps can be adequately retuned. Consequently, margins (e.g., channel spacing) can be reduced while assuring proper Tp operation.

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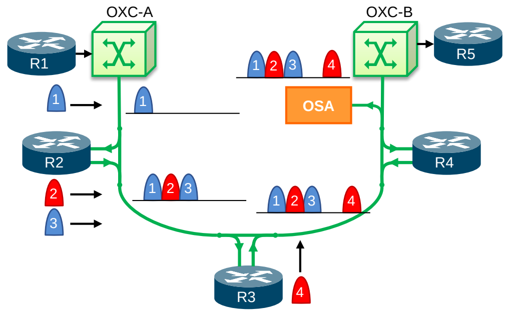

Fig. 1. Example of a FON

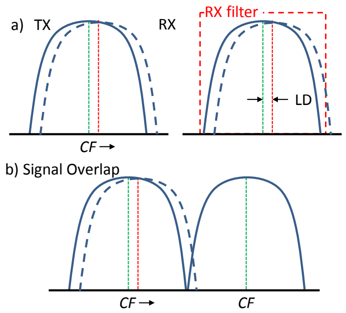

Fig. 2. Signal misalignment and overlap

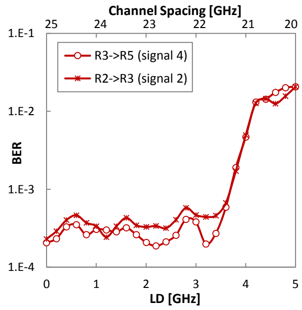

Fig. 3. BER degradation vs LD

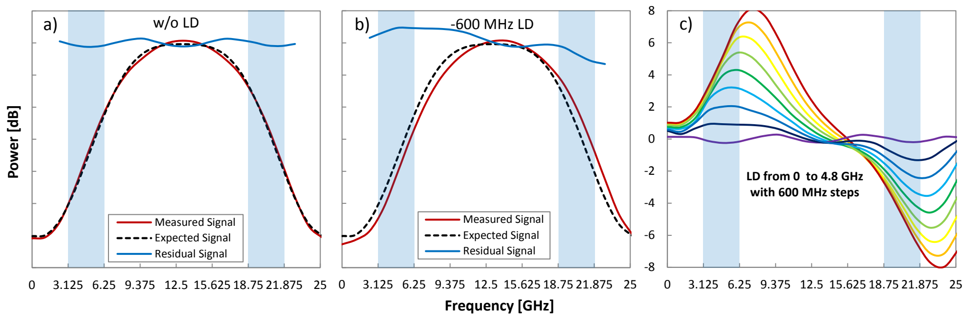

Fig. 4. PAM4 optical spectrum captured by a 1.2 GHz OSA a) w/o LD, b) w/ 600 MHz LD, c) residuals for different LD magnitudes.

While traffic broadcasting is seen as a drawback of FONs, it actually allows using one single OSA installed in the last span to acquire all signals in the FON, as illustrated in Fig. 1. This monitoring solution becomes more beneficial when PAM4 transmission systems are considered. In PAM4, a small detuning of the transmitter leads to a noticeable performance penalty in the receiver; in contrast to coherent systems, DD receivers are not capable of tracking the laser wavelength of the transmitter and any amount of LD results in misalignment between the signal launched by the transmitter and the optical filter in the receiver (see Fig. 2a). LD can potentially produce signal overlap when channel spacing between two neighboring signals is reduced (see Fig. 2b). Misalignments and overlaps ultimately introduce significant performance penalty, as illustrated in Fig. 3 for signals 2 and 4, where simulations were carried out to evaluate the impact of LD over the BER at the receiver (more details are provided in section 4). Note that Fig. 3 might have an alternative lecture; we could reduce up to 3GHz channel spacing provided that very stable systems are deployed in the network.

3. Data analytics procedure for signal tracking

Let us describe the proposed procedure to be triggered when a new spectrum is acquired by the OSA. Active lightpaths are identified following the algorithm proposed in [1]. Next, an LD estimation module is called to check whether all lightpaths are well located and their CFs correspond to what is stored in the controller.

The LD estimation module requires the expected shape and location of every signal in the spectrum. Expected signals are *noise-free* versions of the optical spectrum generated using analytical formulae considering the specific characteristics of every lightpath (i.e., baud rate, shaping-filter in the transmitter, etc. [3]). The measured spectrum of PAM4 signals and their corresponding expected ones are shown in Fig. 4a-b, where a 1.2GHz-resolution OSA was emulated by averaging power values on windows of such width; note that the optical carrier vanished so it cannot be used for LD estimation. Fig. 4a shows a properly configured PAM4 signal, whereas Fig. 4b shows the case when the signal experiences 600 MHz of LD. The next step is to subtract the expected signal from the measured one, which produces a third signal called *residual* signal. If the measured and expected signal are on the same CF, the residual signal oscillates around 0 (Fig. 4a). On the contrary, a positive or negative slope is observed in the residual signal, depending on the direction of the drift (Fig. 4b). For illustrative purposes, Fig. 4c plots the residual signals for LD from 0 to +4.8 GHz with 600 MHz step size.

For modeling the LD estimator, the 3.125 GHz portions of left and right edges highlighted in blue in Fig. 4 were considered as features. These portions are essentially the edges of the spectrum that are expected to be affected due to the LD. Note that in the particular case of Fig. 4, where the traces are based on OSAs of 1.2 GHz resolution, these portions contain only 3 different power-frequency points. The final step is to consider these features and apply multi-variate regression to obtain a model for LD estimation. This procedure works well when the signals are *individually* considered. However, in the case of signal overlap like between signals 2 and 3 in Fig. 1, that procedure needs to be improved, as it finds LD in signal 3, which is actually properly configured. To avoid the effects of spectrum overlap, the LD estimation procedure analyzes the spectrum forward from left to right and considers *contextual* information; once it detects LD in one signal (e.g., in signal

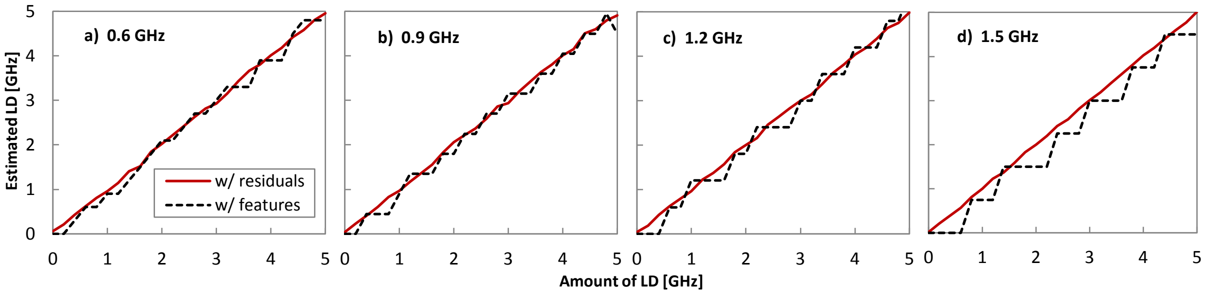

Fig. 5. The tracking accuracy of the optical spectrum

2), it analyzes the following one (e.g., signal 3) considering the actual position of the previous one.

4. Results

For our experiments, we considered a 12.5 GBaud (25 Gb/s) PAM4 for cost-effective metro networks: the electrical shaping filter of the transmitter is modeled as a 12.5GHz root-raised-cosine (RRC) shaping with mild roll-off factor of 1, driving a Mach-Zehnder Intensity Modulator with 30dB extinction ratio. Propagation along 50km of uncompensated standard G.652 SMF is considered, including EDFAs to compensate for losses; OSNR is set equal to 28dB. At the receiver, the desired channel is extracted through a 25GHz optical filter modeled as in [4]. Optical power at the receiver is -10dBm and a post-detection RRC filter with roll-off 1 and 10GHz bandwidth is applied on the photodetected signal; thermal noise from photodetectors is also included. BER measurements are performed by means of symbol-by-symbol hard threshold detection; no DSP is performed on the acquired waveforms prior to BER measures, except timing recovery to find the optimum decision point within the symbol time, as well as the optimum decision thresholds.

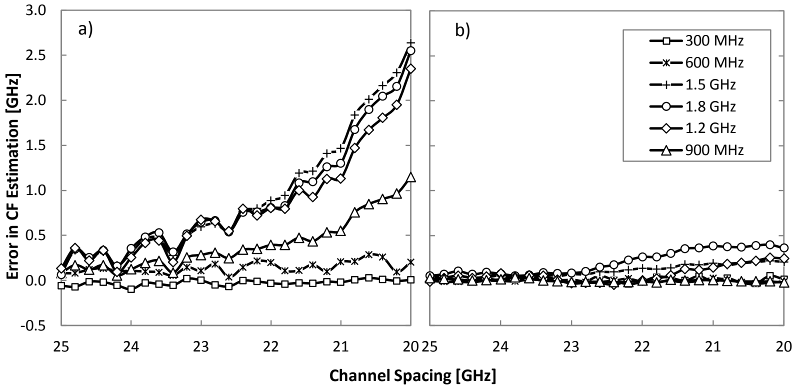

Fig. 6. Tracking accuracy with a) individual signal analysis and b) contextual analysis.

In the first set of experiments, we focus on analyzing one single PAM4 signal (labeled as signal 4 in Fig. 1) that is simulated to drift right with steps of 200 MHz up to 5 GHz; the BER degradation was plotted in Fig. 3, where after 3 GHz of LD, the BER starts to increase sharply due to detuning w.r.t. the receiver optical filter. We carried out LD estimation considering OSAs of different granularities; the results are plotted in Fig. 5. For benchmarking purposes, we also obtain the estimations following the procedure proposed in [1] (labeled *w/ features*). As shown, the estimation accuracy of the residual based approach is almost perfect regardless of the OSA resolution, while the accuracy of the other approach degrade as OSA of coarser granularity is considered.

In the second set of experiments, three PAM4 signals spaced 25 GHz are modeled. Similarly to Fig. 1, the CF of the central one (signal 2) is detuned towards the channel on the right (signal 3) with steps of 200 MHz up to the point their spacing becomes 20 GHz. Now, we are interested in evaluating whether the proposed approach enables reducing the channel spacing to reduce the margins. In this case, LD estimation for signal 2 works as accurate as in the previous experiment for signal 4. However, when the individual analysis procedure is applied to analyze signal 3 we observed that the accuracy was poor; the results are presented in Fig. 6a, where the estimation error is plotted as a function of the spacing between the signals. These results are as a consequence of part of signal 2 overlapping signal 3, which for coarse-granular OSA produces a significant loss of accuracy. Fig. 6b presents the results obtained when contextual analysis is applied. After finding that signal 2 presents some amount of LD, the contextual approach generates an estimated signal that takes into account such fact. This contextual expected signal generates residuals that counteract the effects of signal overlapping and allows to preserve the accuracy observed in the first set of experiments. In fact, is that extraordinary accuracy what enables reducing channel spacing, as any slight LD can be detected and procedures for laser retuning triggered.

5. Conclusions

A novel procedure for optical signal tracking has been proposed; it estimates CF shifting with an accuracy of 100s of MHz analyzing captures acquired by OSAs with granularities as coarse as 1.8 GHz. Considering the proposed procedure, FON channel spacing can be narrowed enabling lower margin operation.

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