

Real-time Spectrum Surveillance in Filterless Optical Networks

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Abstract: A monitoring system exploiting data analytics and cost-effective optical spectrum analyzers with under 1.2GHz resolution is proposed. Its performance is demonstrated in a filterless network experimental test-bed. The system enables prompt action before lightpath disruption.

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OCIS codes: (060.0060) Fiber optics and optical communications, (060.1155) All optical networks

1. Introduction

Filterless optical networks (FON) have recently attracted significant attention as a cost-effective metro solution to interconnect 100G coherent-based nodes in a drop and waste network architecture [1]. FONs can also perform very well in small size regional and submarine transmission networks. Note that, since the operating lightpaths do not pass filtering nodes, FONs can be considered as a kind of *gridless* network where frequency slots are not rigidly defined, which could drive to a better use of spectrum resources; the downside is that (un)intentional laser drift of a tunable transponder (Tp) can disrupt proper operation of a neighboring lightpath. This is in contrast to spectrum switched optical networks (SSON), where laser drift effects are much more moderate. Therefore, cost-effective approaches to monitor FONs are needed to allow network operators to take prompt actions in case of improper operation of a device in their domain. Most of the current surveillance systems rely on the capabilities of coherent receivers to collect measurements [2]. Regardless of their complexity, these approaches limit the performance of surveillance systems, which are intended to monitor the whole domain in real-time with the minimum extra cost and complexity. With the development of cost-effective optical spectrum analyzers (OSAs) with sub-GHz resolution [3] deployable in the optical nodes, a new horizon has been seen for the development of surveillance platforms that can benefit from the optical spectrum captured by OSAs. OSA resolution is related to its cost and therefore, a target OSA resolution should be studied. Due to the broadcast nature of FONs, just one OSA per fiber is enough to capture the aggregated spectrum. Therefore, remarkable cost savings can be achieved by properly delimiting their target resolution.

In this paper, we propose to use OSAs in FON to continuously scan the whole C-band and study the most appropriate OSA resolutions. The acquired spectrum is then processed by a set of low-complexity machine learning algorithms implemented in the network nodes, aiming at monitoring the healthiness of the active lightpaths and detecting failure ahead of having a service disrupted. To the best of our knowledge, this is the first work focusing on monitoring in FON, specifically addressing impairments that are not so critical in SSON.

2. Real-time spectrum surveillance in FONs

In contrast to SSONs, FONs eliminate or minimize the number of active switching elements in the optical line systems. An example of FON connecting packet nodes is presented in Fig. 1. FON nodes (FN) 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 five lightpaths are created (R1->R2, R1->R3, R2->R4, R3->R5, and R5->R6). Let us imagine that Tp in R3 experiences a problem where the central frequency (*CF*) of the R3->R5 signal drifts to the right; in this case, lightpath R5->R6 will be affected since the spectrum of lightpath R3->R5 overlaps it, even though the spatial route of the two lightpaths do not intersect. As a result, a surveillance method should be considered to detect laser drifts, while determining whether a drift will impact a neighboring lightpath. Our proposal has an advantage while exploited for FONs, which is the small number of OSAs required for real-time network spectrum monitoring; note that in a similar SSON, one OSA per link (five in total) would be required. In this work, we propose to use one single OSA installed in the last span, where all signals in the FON can be acquired. Captured spectrum needs to be analyzed real-time so active lightpaths in the FON are monitored and prompt actions are taken before a properly operating lightpath becomes affected by a failed Tp. Therefore, we assume the distributed hierarchical monitoring and data analytics architecture in [4], which includes computation capabilities close to the network nodes.

Note that the frequency range of a signal might not be exactly determined and slightly change along

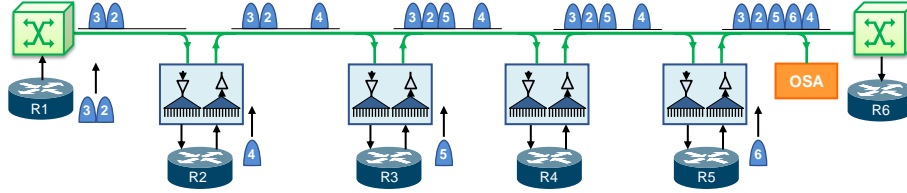


Fig. 1. Example of a FON created between two OXC, where one single OSA captures the aggregated spectrum.

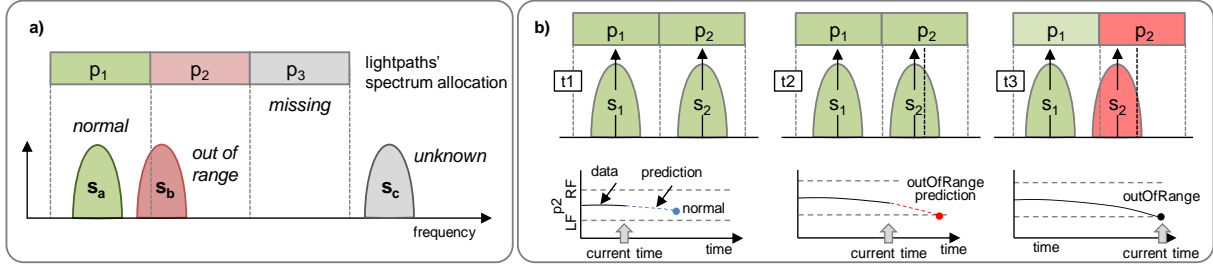


Fig. 2. Signal classification example (a) and anomaly prediction (b)

lightpaths' lifetime. Therefore, an algorithm examining the captured optical spectrum cannot select a frequency range in the whole C-Band acquired by an OSA and focus on analyzing it in the hope that the whole spectrum of a target lightpath and only of such lightpath is confined within that frequency range. In consequence, in the next section, we propose algorithms that periodically scan the whole C-band and rely on an ordered list of lightpaths, including relaxed frequency ranges for each one, obtained from the SDN controller; the scan process is intended to ensure that signals in the network and lightpaths in the list match in terms of frequency ranges. Any found difference (i.e., signals not in the list and lightpaths not in the FON), as well as detected anomalous signal CF shifts that might end in impacting neighboring lightpaths are reported to the SDN controller. Analyzing the current signals' spectrum allocation and lightpaths information from the controller, we thus aim at checking whether each signal is confined within the frequency range allocated to a lightpath (*normal* signals); conversely, three anomalies can be identified (illustrated in Fig. 2a), namely: *i*) a signal is partially out of the spectrum allocated to a lightpath (*outOfRange*); *ii*) a signal is in a spectrum range not allocated to any lightpath (*unknown*); and *iii*) no signal has been detected in the spectrum allocated to a lightpath (*missing*). The detection of any of these anomalies triggers a notification with *critical* severity level to the controller, whereas *normal* signals need to be tracked afterwards to predict a potential anomaly.

3. Data analytics procedure for anomaly detection in filterless networks

The proposed data analytics procedure starts when a new C-band scan is acquired by the OSA, which generates an ordered list of *frequency-power* pairs. The first step is to detect the allocated spectrum to each signal; by using the derivative of the power w.r.t. the frequency [5], the sharp power rising at the left frequency edge followed by the power falling at the right frequency edge of each signal in the spectrum can be detected. Next, the algorithm in Table 1 is used to classify the set of identified signals S w.r.t to the list of lightpaths P .

After some initializations (lines 1-3), the algorithm iterates on the signals to find the lightpaths where the allocated spectrum includes part of their range (lines 4-5); if no lightpath is found, the signal is classified as *unknown* (line 6), whereas it is classified as *normal* if the allocated spectrum of just one lightpath totally overlaps the signal (lines 7-9). Otherwise, signals are classified as *outOfRange* and assigned to the first overlapping lightpath if more than one exists (lines 10-16). Finally, the set of *missing* lightpaths (if any) are obtained and the classification results eventually returned (lines 17-18).

Non-*normal* signals trigger notifications to the controller and they can be discarded for further analysis. The next step focuses on tracking *normal* signals to predict any possible violation of their spectrum allocation that could impact on neighboring signals. In this step, the optical spectrum of each signal is analyzed to find relevant points, such as the *CF* and the left and right frequencies (*LF/RF*) computed at -3dBs [5]; the relevant points are used to track the evolution of the signal with time and to predict whether it is likely to exceed the spectrum allocation within a given future time window. An example of this procedure is illustrated in Fig. 2b, where signal s_2 is gradually approaching neighboring signal s_1 . In this case, the prediction of s_2 *LF* at time t_2 states

Table 1 Signal Classification Algorithm

INPUT	S, P
OUTPUT	$normal, outOfRange, missing, unknown$
1:	$normal=outOfRange=missing=unknown←\emptyset$
2:	$ID←getAllIds(P)$
3:	$S'←\emptyset$
4:	for each $s∈S$ do
5:	$P'←findOverlappingLightpaths(P, s)$
6:	if $P'≠\emptyset$ then $unknown←unknown ∪ \{s\}$
7:	else if $ P' =1$ and $totalOverlap(s, P')$ then
8:	$normal←normal ∪ \{<P'.getId(), s>\}$
9:	$ID←ID \setminus \{P'.getId()\}$
10:	else $s.I←P'.getId()$
11:	$S'←S' ∪ \{s\}$
12:	if $S'≠\emptyset$ then
13:	for each $s∈S$ do
14:	$I←\{s.I\} ∩ ID$
15:	$outOfRange←outOfRange ∪ \{<I.first, s>\}$
16:	$ID←ID \setminus I.first$
17:	if $ID≠\emptyset$ then $missing←missing ∪ ID$
18:	return $normal, outOfRange, missing, unknown$

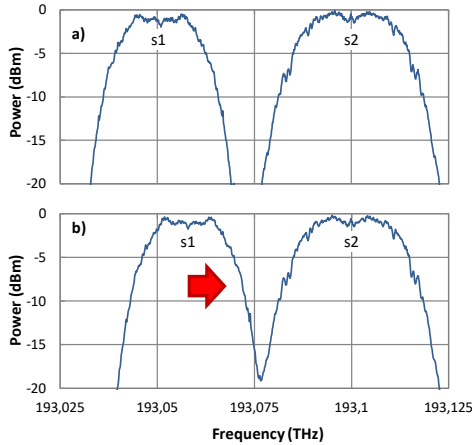


Fig. 3. Optical spectrum under normal conditions (a) and when laser drift causes overlapping (b).

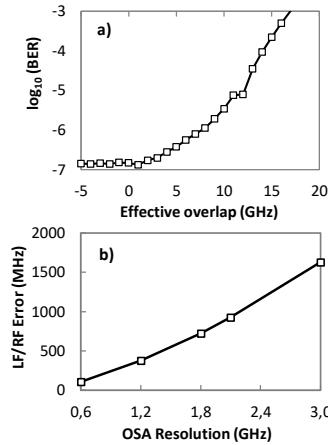


Fig. 4. BER degradation vs. shifting (a). LF/RF error vs OSA resolution (b).

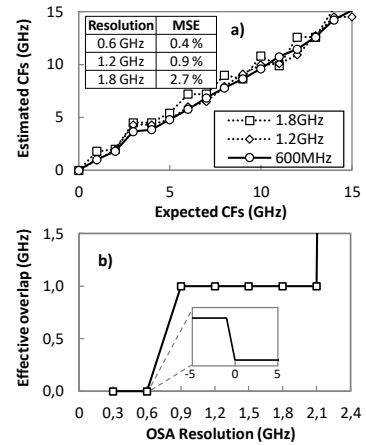


Fig. 5. OSA resolution for CF tracking (a) and overlap detection (b).

that it will exceed its spectrum allocation and thus, a notification with *warning* severity level is triggered towards the controller before an *outOfRange* anomaly is detected (which actually happens at time t_3).

4. Results

To validate the algorithms for real-time spectrum surveillance in FONs, we setup an experimental test-bed where two neighboring 100 Gb/s signals (labeled as $s1$ and $s2$) were launched. Signal $s1$ was generated using an experimental system, while signal $s2$ was generated by a commercial system. Signal $s2$ was considered to operate properly, while $s1$ is forced to move toward the neighboring one at 1 GHz steps from an initial 6 GHz spacing between signals (Fig. 3), simulating a laser drift failure. Due to the filterless characteristics of the network, signal $s2$ is affected after a certain amount of laser drift. Fig. 4a shows the pre-FEC BER of signal $s2$ as a function of the overlap with signal $s1$ (negative values indicate the amount of bandwidth between their spectra). A sequence of C-band spectra was acquired using a commercial OSA with 100 MHz resolution; a number of captures with coarser resolution, from 300 MHz to 3 GHz, were subsequently generated from the original capture to analyze the impact of the resolution on the accuracy of the proposed algorithms.

Selecting the spectra in Fig. 3, the signal classification algorithm perfectly identifies both signals and matches them to two existing lightpaths; the algorithm classifies as *normal* signals when it analyzes the spectrum in Fig. 3a, whereas it identifies $s1$ as *outOfRange* when analyzes that in Fig. 3b. Nonetheless, it is worth studying the accuracy of signals' detection vs. OSA resolution. To that end, we emulated 5000 different lightpath frequency ranges for every spectrum capture with no overlap. The accuracy on *LF* and *RF* computation vs. OSA resolution are reported in Fig. 4b and the results of the *CF* computation for three OSA resolutions are reported in Fig. 5a, where the inner table inside Fig. 5a details the mean squared error (MSE) for each OSA resolution. It is clear that the finer the OSA resolution the lower the error in points computation, which impacts on signal identification.

Let us now study the accuracy of signal overlapping detection as a function of the OSA resolution. In this case, we track *LF*, *CF*, and *RF* to infer when both signals begin to overlap. Fig. 5b shows the results of the detection; with 300 MHz and 600 MHz OSA resolution, the overlap is perfectly detected; the inner graph inside Fig. 5b shows how the sudden change in LF of signal $s2$ allows detecting the overlap. When OSA resolution is up to 2.1 GHz, 1 GHz of effective overlap is needed to detect it, whereas the overlap is not detected for coarser OSA resolutions. Therefore, 1.2 GHz OSA resolution can be identified as the coarser one for accurate signal tracking and overlap detection.

Finally, we analyzed the sequence of spectra with resolution 1.2 GHz in Fig. 3 during the prediction step by tracking *LF*, *CF*, and *RF* of the signals to anticipate whether they may experience any kind of anomaly; overlap was predicted after analyzing a sequence of 3 spectra with 1 GHz laser drift, thus anticipating overlap 4 GHz before it actually happened and enabling the SDN controller to timely restore nominal operating conditions.

5. Conclusions

A data analytics based surveillance system that uses the optical spectrum to detect failures has been proposed. The performance of the proposed procedure has been demonstrated while applying to the measurements captured from an experimental test-bed of a filterless network. Ultimately, the minimum required resolution of OSAs to accurately track signals and to detect signal overlap was determined to be not coarser than 1.2 GHz.

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