Demonstration of Multi-channel Hitless Defragmentation with Fast Auto-tracking Coherent RX LOs

Chuan Qin†, Roberto Proietti, Binbin Guan, Yawei Yin, Ryan P. Scott, Runxiang Yu, and S. J. B. Yoo‡
†Department of Electrical and Computer Engineering, University of California, Davis, One Shields Ave., Davis, California, 95616, USA
‡chaqin@ucdavis.edu, ‡ybwoo@ucdavis.edu

Abstract: This paper demonstrates simultaneous defragmentation of two channels without causing errors (BER < 10⁻¹⁵) on other connections lying in the middle. The technique exploits fast tunable lasers and burst-mode coherent receivers with fast wavelength auto-tracking.

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1. Introduction

Elastic Optical Networking (EON) [1] is a promising way to utilize spectrum efficiently by allocating bandwidth and modulation format on each flow. It replaces the fixed wavelength grids with arbitrarily assigned spectral slices to support various bandwidth needs from sub-wavelength to super-wavelength transmission. However, the network may suffer spectral fragmentation due to dynamic traffic demands seeking flexible spectrum allocations, much like the way computer hard disks becoming fragmented. Spectral fragmentation results in high blocking rates and low utilization of network capacity. Defragmentation techniques aim to solve this problem by re-assigning existing connections to a new bandwidth location. Previous works for defragmentation utilized make-before-break (MbB) [2] or push-and-pull [3] and wavelength sweeping [4] methods, but MbB requires additional transmitter and receiver pairs and the others fail to achieve complete defragmentation without interfering with other connections. Recent work [5, 6] demonstrated a defragmentation scheme using fast tunable laser with blanking and real-time wavelength tracking at the receiver. We will call this ‘hop tuning’ method in this paper. The results show that it is possible to defragment a single-channel connection very quickly (<1μs) without data loss (hitless in terms of service and data bits) by using a small link-layer buffer (few KBytes) and a fast wavelength auto-tracking scheme for the local oscillator (LO) in the coherent receiver. Table 1 shows a comparison between hop tuning and the sweeping method in [4]. Based on hop tuning, this paper demonstrates the simultaneous hitless defragmentation of two 10 Gb/s QPSK channels without causing errors on a connection that is spectrally located in between the initial and final spectrum location.

<table>
<thead>
<tr>
<th>Table 1 Comparison of defragmentation techniques</th>
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<tbody>
<tr>
<td>Hop Tuning</td>
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<tr>
<td>Number of channels defragmented at a time</td>
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<tr>
<td>Defragmentation sequence</td>
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<tr>
<td>Defragmentation speed</td>
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2. Networking Scenario and Defragmentation Experiment Testbed

Fig. 1(a) shows a three-node network scenario with five available wavelengths for the defragmentation experiment. Fig. 1(b) shows the spectrum location before and after the defragmentation happens. At the beginning a user needs to setup two connections from node 1 to 3 but there are no contiguous spectrum slots available on λ₁ and λ₂. If defragmentation enables connection A and B to hop over the existing connection C at wavelength λ₃, then λ₁ and λ₂ become available for the new connections. Fig. 1(c) shows the defragmentation steps including wavelength selective switch (WSS) reconfiguration, the defragmentation of connections A and B and the setup of two new connections F and G.

Fig. 2 shows the experiment testbed which implements the three-node network scenario in Fig. 1(a), and employs limited experimental apparatus including one dual-polarization optical hybrid, one real-time scope, and polarization multiplexing, which is not used here for doubling the channel capacity but for being able to receive simultaneously the two channels under defragmentation (only one optical hybrid was available). The link starts with two tunable laser diode (TLD) transmitters modulated by an I/Q modulator. The TLDs approximately have 2MHz linewidth and the output power is 0dBm. The FPGA drives the I/Q modulator with two 5Gb/s RF binary signals and the data correspond to 2⁷-1 PRBS 10Gb/s QPSK signals. After modulation WSS₁ splits the two channels and a PBS combines the two channels orthogonally in polarization before an EDFA amplifies and launches them into a 25km
SMF. At the receiver, part of the signal power goes into an athermal AWG with 100GHz channel spacing. The AWG, O/E converter and the comparator combine to detect a rising edge at the target wavelength and to tell the FPGA about the change. Once it gets this information, the monitoring FPGA will send a control signal to the LOs to track the wavelengths of TX TLDs[5, 6]. The rest part of signal enters a coherent receiver with offline digital signal processing (DSP). The signal and reference waves enter a dual-polarization optical hybrid, and the four outputs from the balanced detectors are real and imaginary part of the two channels respectively. In the intermediate connection which represents connection C in Fig. 1, a laser is modulated by Mach-Zehnder Modulator (MZM) with a 10Gb/s OOK signal at λ3. The receiver is a 10Gb/s error analyzer (EA). A switch on the FPGA triggers the defragmentation by switching RX1 from λ1 to λ4 and RX2 from λ2 to λ5. The spectrum on the bottom left corner of Fig. 2 shows the laser profiles before and after the defragmentation. Before the defragmentation two carrier frequencies are 300GHz apart but after that they are 100GHz apart and the spectrum becomes more compact. During the switching the EA monitors the BER for the connection C.

![Fig. 1](image1.png)

(a) Three-node network scenario: EOTN - elastic optical transponder; WSS: wavelength selective switch; NC&M: network control and management. (b) Spectrum location before and after defragmentation. (c) Defragmentation steps and spectrum allocation between node 2 and 3.

![Fig. 2](image2.png)

Hitless defragmentation experiment testbed and WSS configuration. MZ Mod: Mach-Zehnder Modulator; FPGA: field programmable gate array; PC: polarization controller; PBS: polarization beam splitter; O/E: Optical to electrical converter Comp: comparator; EDFA: erbium doped fiber amplifier. BPF: band pass filter; LO: local oscillator; DCF: dispersion compensation fiber; SMF: single-mode fiber; EA: error analyzer.

### 3. Experimental Results and Testbed Performance

Fig. 3(a) shows the BER results of the simultaneously defragmented two channels. We measure the back-to-back case as a reference along with the case with 25km SMF for both defragmentation and static (where wavelength does not change) scenario. The BER is at the $10^{-3}$ level when OSNR is approximately 28dB. Fig. 3(b) shows the BER vs. data recovery time for both channels. It takes 6μs after defragmentation happens for the BER of channel 2 to reach below $5\times10^{-4}$, and this time for the channel 1 is 27μs. Fig. 3(c) gives the constellation corresponding to the points in Fig. 3(b). The constellation becomes less noisy as the starting point of the measurement moves forwards. The reason for slow stabilization time of channel 1 is that TLDs on this channel need greater driving current which may cause thermal issue, and the wavelengths stabilize slowly. The performance of TLDs has significant impact on the BER and data recovery time. If the frequency difference between transmitter and LO lasers changes over time, the linear phase in time domain becomes a challenge to the DSP of the signal. The obvious difference of the data recovery time between two channels suggests that fast stabilization of wavelength for TLD is always favorable. Replacing the two TLDs on channel 1 with lasers whose wavelength can stabilize within several micro-second gives a great chance
to have short data recovery time (e.g. 3.2μs corresponding to 4KB buffer size) on both channels. Higher data rates instead of 5GBaud would reduce the number errors as well because the influence of phase noise from the laser will cause fewer problems. The crosstalk coming from the other polarization also leads to degradation of signal. At the receiver of the intermediate connection C, an EA monitors the real-time BER of this connection. To study the impact of defragmentation of adjacent connections A and B, we replace WSS2 with a 3dB coupler to emulate a colorless ROADM. The EA shows zero accumulated error in one-minute time window (resulting in a BER below 10^-4) during which several operations of defragmentation tuning wavelengths back and forth are attempted. The explanation is that the switching happens rapidly within several hundred picoseconds or even less. The energy in this short amount of tuning time compared to the strong signal energy causes few, if any, bit errors.

![Figure 3](image1.png)

Fig. 3 (a) BER of both channels for back to back and with 25km SMF case under static and defragmentation condition. (b) BER vs. data recovery time for channel 1 and channel 2. (c) Constellation vs. measurement starting time after defragmentation happens for both channels.

4. Conclusions
The proposed technique enables the simultaneous defragmentation of multiple channels without causing any errors on existing connections lying in between the original and target wavelength locations. During the defragmentation, real-time average BER reaches below 10^-4 less than 30μs after initiating defragmentation. With 25.6μs data pause time, which corresponds to approximately 30kB buffer size required at 10 Gb/s, this experimental method can support hitless defragmentation seen at the service layer. Higher data rates will reduce the impact of phase noise of TLDs and lead to less penalty and shorter data recovery time, while requiring correspondingly larger buffer memory to support service-layer hitless defragmentation.

5. References