A Centrally Controlled Survivable WDM-PON Based on Optical Carrier Suppression Technique

Yang Qiu, Zhixin Liu, and Chun-Kit Chan

***Abstract*—A simple centrally controlled survivable wavelength-division-multiplexed passive optical network (WDM-PON) architecture employing an optical carrier suppression technique is proposed. Protection switching at the optical line terminal employs electrical switches to control the clock signal for the protection subcarrier generation, via optical carrier suppression. Both distribution and feeder fibers are protected simultaneously. By employing an inverse-return-to-zero format for the downstream transmission and nonreturn-to-zero for the upstream remodulated signal, the optical network units are kept colorless and simple. The 10-Gb/s transmissions under both normal working and protection modes were experimentally demonstrated and traffic restoration time was measured to be about 5 ms.**

***Index Terms*—Optical carrier suppression, passive optical network (PON), wavelength-division multiplexing (WDM).**

I. Introduction

THE wavelength-division-multiplexed passive optical network (WDM-PON) is an attractive solution to realize optical broadband access. In order to avoid enormous data loss due to any possible fiber cuts, survivable network architecture is highly desirable. Recently, several interesting schemes [1]–[6] have been proposed to provide protection and restoration functions in WDM-PONs. In [1], [2], survivable WDM-PONs were realized either through the periodic wavelength routing properties of array waveguide grating (AWG) [1], or the self-protection between the grouped optical network units (ONUs) [2], which required optical switches at the ONUs. Although some centrally controlled protection architectures have been proposed in [3], [4], dedicated light sources for downstream and upstream transmissions were needed. In [5], a large number of optical interleavers were required for protection path routing in a survivable WDM-PON, in which optical carrier suppression (OCS) [6] was employed to generate optical subcarriers for the upstream transmission.

In this letter, we propose a simple and centrally-controlled, survivable WDM-PON architecture with colorless ONUs. The proposed protection switching mechanism is based on alternate path routing of optical subcarriers generated by applying OCS technique to the light source in each transmitter at the optical line terminal (OLT). No additional dedicated light source for protection switching is needed. Only electronic switches, instead of optical ones, are required at the OLT to trigger the control clock signal in the OCS process, thus fast traffic restoration is guaranteed. Both the distribution and the feeder fibers are protected against the possible fiber cut failure. Besides, by employing inverse-return-to-zero (IRZ) [7] format for the downstream transmission and nonreturn-to-zero (NRZ) format for the upstream remodulation, the ONUs remain colorless and simple. We have experimentally demonstrated 10-Gb/s transmissions both in normal working and protection modes and has achieved short traffic restoration time.

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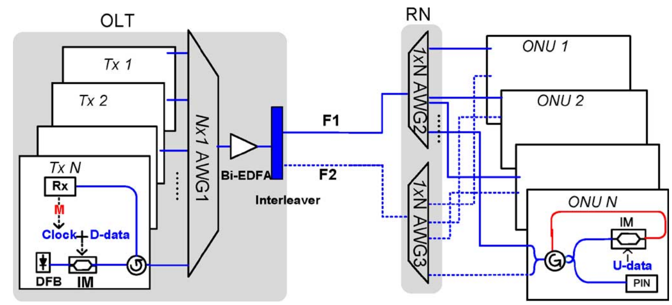

Fig. 1. WDM-PON with proposed multicast overlay scheme. IL: Optical interleaver. M: Monitoring unit.

II. Proposed Survivable WDM-PON Architecture

Fig. 1 depicts the proposed centrally-controlled survivable WDM-PON architecture with N ONUs. At the OLT, continuous wave (CW) light from each transmitter is first fed into a Mach–Zehnder intensity modulator (IM), biased at null transmission point, and driven by a composite signal of a control clock and the downstream data (D-data). The peak-to-peak voltage (V_{pp}) of the driving composite signal should be twice of the half-wave voltage (V_{π}) of the IM. In this way, the optical central carrier is suppressed, while the two generated sidebands (optical subcarriers) are carrying the downstream data in IRZ format. This is also known as OCS-IRZ format. Under normal working mode, the control clock signal is off. Thus, OCS is not enabled and the original input optical carrier works as the normal downstream carrier. However, when a fiber failure is reported either in feeder or distribution fiber, by means of monitoring the power outage of the respective received upstream signal at the OLT, the clock signal is turned on to generate OCS-IRZ downstream data in protection mode. The downstream wavelengths, either the central carrier under normal working mode or the generated optical subcarriers under protection mode, are then combined with all other modulated ones from other optical transceivers at the OLT, via an $N \times 1$ AWG (AWG1). Under protection mode of one particular

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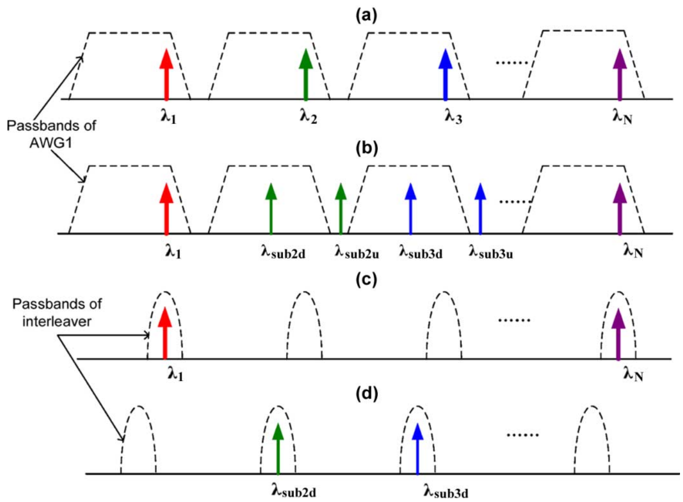

Fig. 2. Spectra of downstream carriers to illustrate the protection principle, assuming that fiber failures have been detected along the lightpaths of λ_2 and λ_3, for example. (a) Input CW carriers; (b) output of IM; (c) even port of the interleaver, connected to feeder F1; (d) odd port of the interleaver, connected to feeder F2.

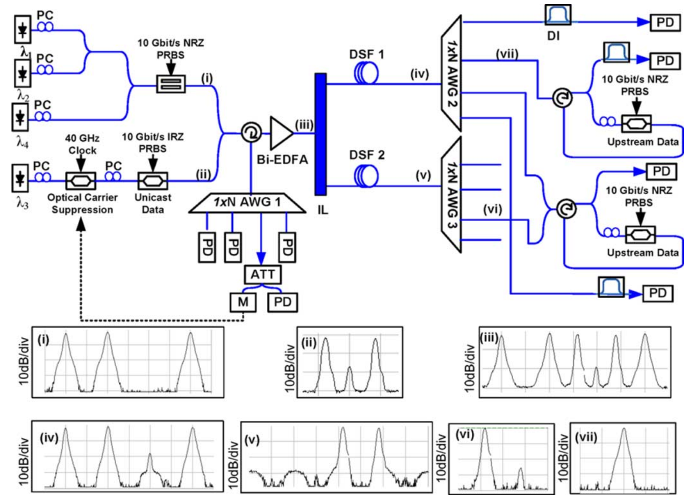

Fig. 3. Experimental setup. DSF: Dispersion-shifted fiber. Bi-EDFA: Bidirectional erbium-doped fiber amplifier. Insets show the spectra when channel 3 is in its protection mode. Horizontal scale: 0.4 nm/div.

optical transmitter, one of the generated optical subcarriers falls outside the transmission passband of the AWG1 and is largely suppressed, while the other one remains and is forwarded to the output port of the AWG1. The downstream wavelengths are then amplified by a bidirectional Erbium-doped fiber amplifier (EDFA), which can be constructed by two conventional EDFAs and two optical circulators. The amplified composite signal is then fed into an optical interleaver (IL), where the central carriers under normal working mode and the generated optical subcarriers under protection mode are delivered to the remote node (RN) over the fiber feeders, F1 and F2, respectively, before they are further demultiplexed at the RN, via $1 \times N$ AWG2 and $1 \times N$ AWG3, respectively. These demultiplexed carriers are then combined at their respective destined ONUs, via two sets of distribution fibers. At each ONU, the received downstream wavelength is tapped off by a 3-dB optical coupler, where half of the received optical power is directly detected to retrieve the downstream data, while the other half is fed into an IM for upstream data (U-data) remodulation in NRZ amplitude shift-keying (ASK) format. The upstream signal is then delivered back to the respective receiver unit at the OLT, where part of the received upstream power is fed into the monitoring unit (M) for fault monitoring. Any reported fault alarm (prolonged power outage) triggers the control clock signal for OCS and activates the protection mode.

Fig. 2 shows the downstream optical spectra to illustrate the principle of the protection mechanism. Fig. 2(a) shows the wavelength assignment of all input CW carriers $(\lambda_1, \ldots, \lambda_N)$, and the transmission passbands of the AWG1 at the OLT. It is assumed that fiber failures have been detected along the lightpaths of both λ_2 and λ_3, for instance. For the optical carriers under normal working mode (say $\lambda_1, \lambda_4, \ldots, \lambda_N$), the monitoring units at the respective transceivers at the OLT turn off their clock signals in order to disable the OCS process, and thus only the original input central carriers exist for the downstream transmission. Due to the spectral separation property of IL, the normal working central carriers are delivered on the normal working path, which includes the feeder F1, AWG2 and the respective distribution fibers, via the even port of the IL, as illustrated in Fig. 2(c). On the contrary, for the optical carriers under protection mode (say λ_2, λ_3), the monitoring units at the respective transceivers at the OLT trigger the clock signal to generate the respective OCS-IRZ spectra, as shown in Fig. 2(b). With the filtering effect of the AWG1, only one of the two generated optical subcarriers in each case is selected and utilized as the protection carrier for downstream transmission. Due to the wavelength shift introduced by OCS, the protection carriers are switched to the protection path (including the protection feeder F2, AWG3 and the respective distribution fibers), via the odd port of the IL, as illustrated in Fig. 2(d). The working and the protection paths are finally combined at the respective destined ONUs. As a result, the possible failures in either feeders or distribution fibers along the individual lightpaths are protected, simultaneously.

III. Experiment and Results

Fig. 3 shows the experimental setup of a four-wavelength WDM-PON, for proof-of-concept of the proposed scheme. The four downstream wavelengths were at Ch1:1546.06 nm (λ_1), Ch2:1546.86 nm (λ_2), Ch3:1547.66 nm (λ_3) and Ch4:1548.46 nm (λ_4). The proposed protection scheme was applied to Ch3 and its CW light was fed into a 40-Gb/s optical IM, driven by a 40-GHz clock signal, which was controlled by the monitoring unit. The frequency of the clock was related to the spectral property of the IL used in the experiment. It could be greatly reduced if an IL with narrower free spectral range was used. The CW light at Ch1, Ch2, and Ch4 were combined before being modulated by 10-Gb/s $2^{31} - 1$ NRZ pseudorandom binary sequence (PRBS), via a 10-Gb/s optical phase modulator, in order to simulate three other in-service modulated wavelength channels in differentially phase-shift keying (DPSK) format, without protection. Under the protection mode of Ch3, the control clock signal was enabled to create two optical subcarriers, λ_{sub1} at 1547.34 nm, and λ_{sub2} at 1547.98 nm; while under its normal working mode, the control clock signal was disabled and only the central carrier

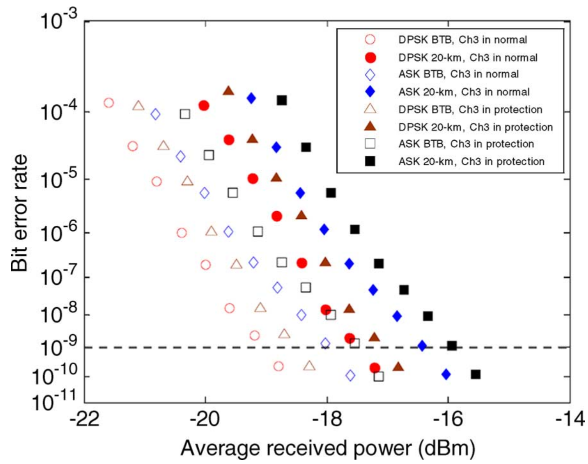

Fig. 4. BER measurements for Ch2.

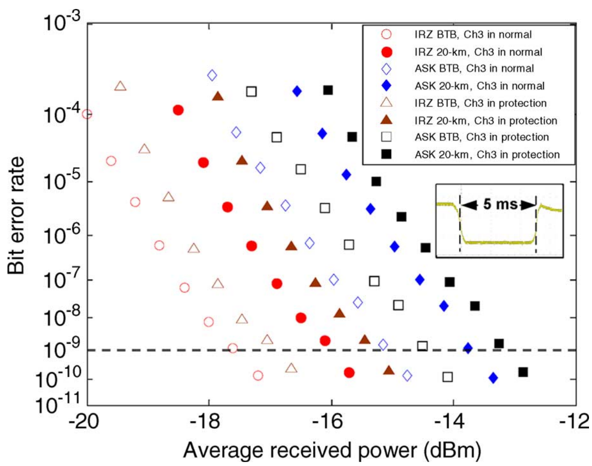

Fig. 5. BER measurements for Ch3.

λ_3, at 1547.66 nm existed. Ch3 were then fed into another IM, driven by 10-Gb/s $2^{31}-1$ PRBS precoded IRZ downstream data, before being combined with other three channels, Ch1, Ch2 and Ch4. The downstream signals were amplified to about 6 dBm, via an EDFA and were forwarded to a 50/100-GHz IL. Under normal working mode, all four wavelengths were fed into a piece of 20-km dispersion shifted fiber (DSF), denoted as DSF1, via the even port of the IL. Under protection mode, only Ch1, Ch2, and Ch4 were fed into DSF1, while the two optical subcarriers, λ_{sub1} and λ_{sub2}, at Ch3 were fed into another piece of 20-km DSF, denoted as DSF2, via the odd port of the IL. DSF was employed to emulate dispersion compensated transmission path. It could be replaced by standard single-mode fiber with dispersion compensating module. The wavelength channels were delivered to their destined ONUs, via AWG2 and AWG3. Under protection mode of Ch3, AWG3 also filtered out λ_{sub2} of the OCS-IRZ signal in Ch3, in order to alleviate the beating effect at the receiver. At the ONU receiving Ch3, half of the received power was used for downstream data detection and the other half was reused for upstream data transmission, via another IM driven by the 10-Gb/s $2^{31}-1$ PRBS upstream NRZ data. The upstream ASK signal was then sent back to the OLT, where part of the received upstream data was fed into the monitoring unit to control the protection switching whenever a power outage was detected.

We have also measured the bit error rate (BER) performances of Ch2 and Ch3, when Ch3 was under its normal working or protection mode. In Fig. 4, about 0.3-dB penalty was observed for Ch2, in all cases of transmissions, between the two operation modes of Ch3, which might mainly due to the nonideal filter effect of the AWG. In Fig. 5, about 0.5-dB degradation was observed for Ch3, in all cases of transmissions, between the two operation modes of Ch3, which might be attributed to the limited optical carrier suppression ratio in the OCS process and the nonideal filtering effect of the AWG, under protection mode. The traffic restoration time was also measured at the monitoring unit, as shown in inset of Fig. 5. About 5-ms switching time was experimentally observed. This switching time was mainly limited by the IM and the electronic switch employed in the experiment.

In our experiment, the power fed into transmission link was about 6 dBm, for the downstream data. The losses induced by fiber transmission, optical circulator, AWG, and optical interleaver were around 5 dB, 1 dB, 4 dB, and 2 dB respectively. Thus the received downstream power for Ch3 was around -12 dBm providing more than 4-dB margin.

IV. Summary

We have proposed and experimentally investigated a simple, centrally-controlled, WDM-PON architecture with colorless ONUs. By using OCS-IRZ format in downstream transmission, protection optical subcarriers are generated, which is controlled at the OLT. The survivable protection architecture can simultaneously protect against the distribution and feeder fiber failures. Error-free transmissions at BER $= 10^{-9}$ for downstream and upstream in either working or protection mode were successfully demonstrated.

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