Frequency Comb and Injection Locking Based Mutual Protections in Coherent Optical Access Network

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Abstract: A P2MP coherent network features mutual protection between adjacent networks, and remote delivery of optical carriers that are injection locked to an optical frequency comb is proposed. System functionality and performance has been verified experimentally. © 2022 The Author(s)

1. Introduction

The ever-increasing demand for bandwidth has been driven by continuous growth of data intensive applications such as 5G Xhaul, HD-video stream, cloud services, and internet of things (IoTs) over the past decade. As a cost-effective solution, passive optical network (PON) based on power splitting has been extensively studied and widely adopted in today's optical access networks [1-4]. Among various access technologies, point-to-multipoint (P2MP) coherent technology is considered as a future-proof solution for next-generation 100G-class PON, thanks to its high sensitivity and powerful digital equalization of fiber transmission impairments [2-4].

As PON data rate evolving towards 100Gb/s/λ, more and more traffic and bandwidth will be carried by the network, protection of key components becomes unprecedently important. Emerging applications in the field of remote health monitoring, telerobotic surgery, autonomous cars, home security and other fields require uninterrupted access service to the end user. Today, existing PON protection schemes usually require complex optical switches and control units [5], or redundant devices such as optical line terminals (OLTs) and backup fiber links [6], which can increase the deployment cost significantly. As a result, although there are many optical protection and restoration architectures implemented in the backbone and metro networks, the present optical access networks are mostly poorly protected or not protected at all. Developing a cost-effective protection scheme is critical to the success of future P2MP coherent network for supporting various traffic needs.

Another major hurdle for large-scale adoption of P2MP coherent network in the access networks is the prohibitively high cost associated with the existing long-haul coherent optics. High quality light sources such as external cavity lasers (ECLs) dedicated for coherent transmitters and local oscillators (LOs) contribute a large portion of the overall cost. For short-haul applications, these expensive devices can be replaced by alternative solutions based on optical frequency comb and optical injection locking (OIL) of low-cost Fabry-Perot laser diodes (FP-LDs) [7].

In this work, we propose a mutually protected P2MP coherent network architecture employing optical frequency comb, OIL, and remote optical carrier delivery. The mutual protection of critical parts such as OLT and feeder fibers in two adjacent P2MP coherent networks can be realized by connecting the passive nodes without requiring complex switching devices or redundant OLT devices. The combined use of optical frequency comb and OIL greatly reduces the number of high-cost lasers in a P2MP coherent network system, the mechanism of remote optical carrier delivery also ensures fast service restoration without requiring wavelength switching for all optical network units (ONUs). System performance and functionality of the protection mechanism have been verified through downstream (DS) and upstream (US) transmission of 100Gb/s data rate coherent signals (from both discrete components and commercial coherent optics) through 50km single mode fiber (SMF) link and cascaded splitters (2×2 + 1×32) in both normal operation and protection mode.

2. Operating Principles and Proof of Concept

Fig. 1 shows the high-level architecture schematic of the mutually protected P2MP coherent access networks with OLT and feeder fiber protection designs in the context of fiber deep environment for majority of operators. Leveraging the high power budget and the wavelength tunability of coherent optics, two adjacent P2MP coherent networks can provide protection to each other by connecting the passive nodes. Under normal operation, the two P2MP coherent networks work at different wavelength, i.e., λ1/λ2 (DS/US) for the upper P2MP coherent network, and λ3/λ4 for the lower P2MP coherent network. Normal feeder and drop fiber links are shown in orange, where protection fiber links are shown in green. Although two P2MP coherent networks are interconnected, by running at different wavelengths the two networks will not interfere with each other. When feeder fiber or OLT device breakage occurs, i.e., if OLT1/fiber link 1 is down, protection activation signals will be sent to all ONUs in the upper P2MP coherent network. All the ONUs that were previously operating at λ1/λ2 will be switched to λ3/λ4, for both transmitters and LOs. OLT2, which is running at λ3/λ4, will now provide DS signals and receive US signals from all the ONUs. Note that the proposed design can be extended to protect multiple P2MP coherent links. The protection port and the regular splitting port can be designed in a flexible way with asymmetric splitting ratios to accommodate different network configurations and application scenarios. Prior to operation, both OLTs and all ONUs will acquire operational parameters for both coherent networks during ranging process.

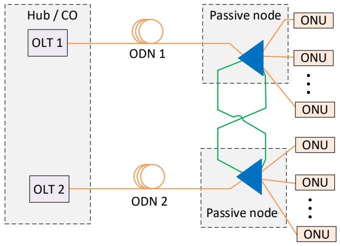

Fig. 1. P2MP coherent network protection design schematic.

	FIT	MTTR
OLT	2500	8 hrs.
ONU	256	8 hrs.
Feeder Fiber	50km x 200/km	24 hrs.
Drop Fiber	2km x 200/km	24 hrs.
Splitter	100	8 hrs.

Table 1. Failure rates and repair time for PON components.

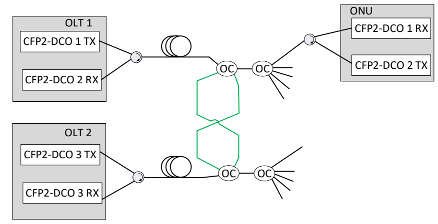

Fig. 2. Proof of concept using commercial coherent transceivers.

Protection of a PON is quantitatively evaluated by its availability, the fraction of time the system or service behaves as intended. For a given system, its availability $A = 1 - \sum_i^N MTTR_i/(MTBF_i + MTTR_i)$, where MTBR defines mean time between failures, and MTTR is the mean time to restore or repair [6]. A goal of the industry is to achieve 99.999% availability, which equivalent to a system being unavailable less than 5.25 minutes in a year. Table 1 shows statistical failure in time (failure frequency in 10^9 hours: $FIT = 10^9/MTBF$) and MTTR for PON components [6, 8]. Based on the parameters in Table 1, an unprotected PON can only have an availability of 99.973%, far from the industrial goal of 99.999%. With the protection scheme proposed in Fig. 1, the MTTR of the feeder fiber and OLT can be significantly reduced, from several hours down to minutes.

As a proof of the concept, we start with testing the mutual protection scheme using commercially available products. Fig. 2 shows an experimental setup using commercial C-formfactor pluggable-digital coherent optics (CFP2-DCO) modules (operating the mode of 100Gb/s date rate). CFP2-DCO 1 is tuned at wavelength λ1 (1548.12nm) and CFP2-DCO 2 is tuned at wavelength λ2 (1548.52nm) for DS and US transmission under normal operation, where CFP2-DCO 3 is used at protection device and tuned to λ1/ λ2 for DS and US protection operation. Initial test using commercial devices verified the functionality of the mutual protection scheme. However, changing US and DS operating wavelengths of all ONUs is still challenging and time consuming, as most of today's commercially available coherent optics are not optimized for fast wavelength switching. For fast service restoration, in our experiment we proposed a P2MP coherent network protection scheme based on optical frequency comb and remote delivery of optical carriers through OIL process. Without requiring ONU wavelength switching, the mutual protection between two P2MP coherent networks can be achieved by tuning an optical filter or wavelength selective switch (WSS). Although our experiment uses discrete components, ultrafast tuning integrated WSS with nanosecond-speed has already been demonstrated [9]. The proposed protection scheme can reach 99.999% availability, with i.e., 50 ms MTTR for OLT and feeder fiber. With this design, one can exceed the 99.999% goal by adding ONU/drop fiber redundancy. In this work, we will be focusing on the OLT and feeder fiber protection. The proposed design can also be applied in the Hub/central office (CO) for OLT protection only, depends on requirements for different application scenarios.

3. Experimental Setup and Results

The schematic of the proposed P2MP coherent network architecture is shown in Fig. 3. On the OLT side, an optical frequency comb is generated by modulating the output of a ECL with a phase modulator followed by a Mach-Zehnder modulator, both driven by a 25-GHz RF signal [7]. Four of the comb tones (λ1: 1563.46 nm, λ2: 1563.86 nm, λ3: 1564.26 nm, λ4: 1564.66 nm) after amplification are filtered out by a WSS with 50-GHz channel spacing to match ITU-T 50 GHz frequency grid. In OLT1 of the upper P2MP coherent network, λ1 is fed into a coherent driver modulator (CDM) (3-dB bandwidth of 40 GHz) to generate DS signals. We use 30GBd DP-QPSK signal targeting 100Gb/s date rate. λ2 is split in two: one is utilized as the LO to detect US signals; the other is combined with DS signals via an optical coupler (OC) and sent downlink through 50 km SMF as optical carrier for US signal generation. The passive node consists of a 2×2 passive splitter cascaded with a 1×32 passive splitter, where the 2×2 splitter provides interconnect between the two P2MP coherent networks. On the ONU side of the link, the remote delivered optical tone (λ2) is filtered out by a tunable optical filter (TOF) and used as the seed light to generate US optical carrier via OIL. The OIL slave laser is a FP-LD, with seed light injected into its cavity via an optical circulator. The generated optical carrier at λ2 is then sent to a CDM for US signal transmission. The DS signals are mixed with a LO at λ1 and detected by an integrated coherent receiver (ICR). The obtained radio frequency (RF) signals for the I/Q components are sent into an optical modulation analyzer acquired at 80GS/s and processed offline with a MATLAB program. DS and US signals at the OLT and the ONU side are routed by corresponding optical circulators. The lower P2MP coherent network operates in the same way, with λ3 for DS and λ4 for US transmission. When network failure occurs, i.e., if OLT1/fiber link 1 is down as shown in Fig. 3(b), DS signal at λ1 will be provided by OLT2 and US carrier frequency will be changed to λ4. In this scheme, wavelength adjustment of all ONUs is not required, network protection can be achieved via fast switching of the WSS.

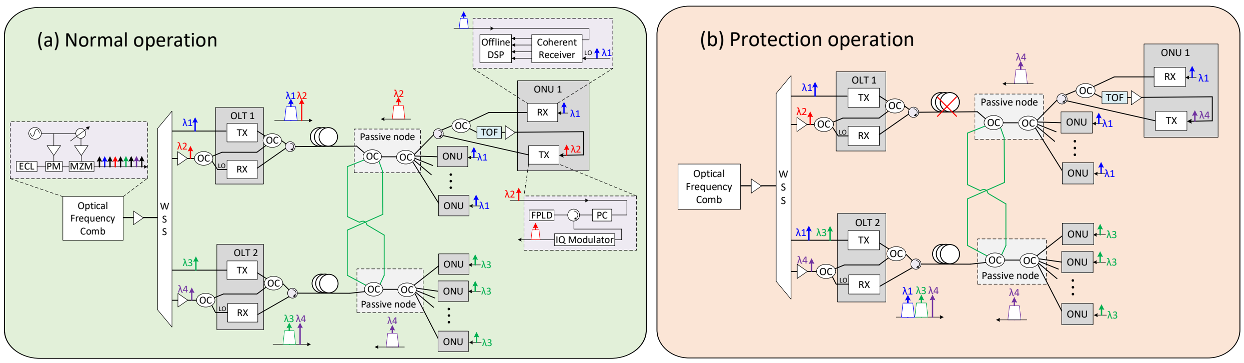

Fig. 3. Experimental system diagram with frequency comb and injection locking photonic process: (a) normal operation; (b) protection operation.

Fig. 4. summarizes the experimental results of the proposed design. Fig. 4(a) shows optical spectrum of the generated optical frequency comb centered at 1563.86 nm with 25 GHz spacing between adjacent tones. Fig. 4(b) shows the spectrum of our DS signals (λ1 and λ3) coupled with the two remote-delivered optical carriers after OIL (λ2 and λ4). Fig. 4(c) and (d) show bit-error-rate (BER) performance versus received optical power (ROP) for the 30-GBd DP-QPSK coherent signal with constellation diagrams, for DS and US transmission. The test has been performed using a variable optical attenuator (VOA) to adjust the received optical power at the coherent receiver. For reference, staircase hard-decision (HD) forward error correction (FEC) threshold (BER=4.5E-3) and concatenated soft-decision (SD) FEC threshold (BER=1.2E-2) are plotted in red. Results for system under normal operation and protection mode, for both back-to-back (B2B) and 50km fiber link are included. From the results, system performances under normal operation and protection mode are very similar, no significant penalty has been observed.

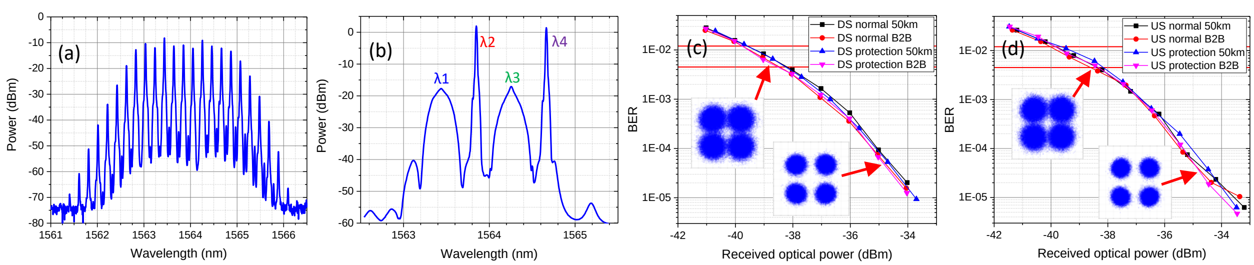

Fig. 4. (a) Optical frequency comb spectrum; (b) spectrum of coherent signals and remotely delivered carriers; (c) downstream transmission BER vs. ROP; (d) upstream transmission BER vs. ROP.

4. Conclusions

In this work, we demonstrate a mutually protected P2MP coherent network architecture without requiring complex switching components, or redundant fiber and OLT devices. With this scheme, system complexity and response time for network protection have been greatly reduced. The combination of optical frequency comb and OIL also significantly reduces the number of high-cost ECLs in the P2MP system. Remote optical carrier delivery ensures fast service restoration without requiring wavelength switching for all ONUs. System performance and functionality of the protection mechanism have been verified through DS and US transmission of 100Gb/s date rate coherent signals through 50km SMF link and cascaded splitters (2×2 + 1×32), in both normal operation and protection mode.

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