In-service monitoring of 16 port x 32 wavelength bi-directional WDM-PON systems with a tunable, coded optical time domain reflectometry

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Abstract: We propose a multi-port, multi-wavelength supervisory system for the in-service transmission line monitoring of a bidirectional WDM-PON system. Identifying unique requirements for the performance monitoring of a real field WDM-PON system, we define the architecture for the supervisory system and utilize the most up-to-date technologies (Simplex coding, tunable source, and optical switches) to demonstrate a successful interrogation of a transmission line up to 16 ports x 32 nodes (512 user) capacity. Monitoring of individual branch traces up to 60 km was achieved with the application of a 127-bit simplex code corresponding to a 7.5dB SNR coding gain. In-service transmission experiments showed negligible penalty from the monitoring system to the transmission signal quality, at a 2.5Gbps / 125Mbps (down / up stream) data rate.

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References and links


1. Introduction

Supporting the sudden rise of Internet data traffic, especially from the user’s end, the conversion of the previous subscriber network to fiber to the home (FTTH) is now on the way in an aggressive manner. In particular, an FTTH solution based on a wavelength division multiplexed passive optical network (WDM-PON) has been the focus of significant attention because of its colorless system architecture, large bandwidth, inherent network security, and expansion capability to new transmission format / services [1, 2]. Considering the huge amount of involved user counts (>16 x 32 = 512) and data traffic amounts (well exceeding Gbps, per a line from the central office), arranged means of monitoring the health of a transmission line from the central office down to every user is imminent, and forms the essential part of the data service itself. Still, with its unique system architecture - supporting multi-port and multi-user / wavelength, the supervisory system for the WDM-PON application now calls for a serious challenge - dictating requirements / specifications that are totally different from those of conventional OTDR (Optical Time Domain Reflectometry):

I: with the large number of users / access lines to monitor, one have to counter the increase in the measurement time.
II: with a different wavelength assigned for each user, one would require a means of directing OTDR probe pulses to different user nodes.
III: considering cost issues and future expansions, it would be better to secure expansion capability for larger numbers of fiber lines.

Solutions for the above stated problems have existed in the past, but in a very limited form, providing only partial solutions. For example, a cost-effective in-situ OTDR, employing a single-mode 850nm vertical-cavity surface-emitting laser (VCSEL) has been suggested for the access and metropolitan area network [3]. Employing an optical switch, a remote fiber test systems (RFTS), also, have been commercialized in the past to monitor multiple numbers of fibers in a sequential manner [4]. For the interrogation of a WDM-PON system, a wavelength-tunable OTDR also has been demonstrated [5, 6]. Still, with the limited number of ports in the optical switch or arrayed waveguide grating (AWG), employed either in RFTS or a tunable OTDR, the total number of users was limited to usually less than several of 10s. The natural extension for the following evolution will be a multi-port, multi-wavelength system combining the RFTS and an AWG together with a tunable OTDR, which will enable coverage of hundreds of users; sharing the system cost, but at the expense of increased network surveillance time. Seems plausible, but considering a simple math, the use of a conventional 3 minute averaging time for tens / hundreds of user lines would make the measurement system impractical making the purpose of in-line monitoring meaningless.

Even if the simplest resolution for the measurement time reduction can be achieved with the increase of the probe pulse peak power, the peak power cannot be increased indefinitely, due to the concurrent nonlinear penalty for the data and increase in the cost [7]. The other approach that can be taken is the use of the recently developed OTDR coding technology [8-11]. For this work, as much as 7.5dB coding gains in the SNR were achieved with the application of 127bit Simplex coding to the OTDR. Considering that the coding gain also can be utilized to reduce the measurement time rather than the dynamic range improvement, significant reductions in the measurement time can be obtained (for example, from 3 minutes to 5.6 seconds with a 127 bit code, ignoring the associated code processing time). Assuming a 16 port x 32 node WDM-PON architecture which we illustrate as an example in this work, this corresponds to a measurement time of less than an hour for the whole network, including 512 users, instead of a day.

In this paper, we demonstrate a multi-port, multi-wavelength supervisory system for the transmission line monitoring of bidirectional WDM-PON systems. OTDR technique, based on the most up-to-date technologies such as simplex coding, tunable source, and an optical
switch were applied to demonstrate fast and reliable interrogation of a transmission line up to the 16 port x 32 node (512 users) capacity. A high speed DSP processor and a parallel data interface were employed in the hardware / firmware to facilitate matrix operations in the decoding process. Monitoring of individual subscriber’s lines for short-reach and long-reach (total link ~ 60km, at 23dB dynamic range) nodes was demonstrated without any transmission penalty to the service traffics (2.5Gbps / 125Mbps: down / up).

2. System description: WDM-PON

Figure 1 shows the schematic diagram of the WDM-PON supervisory system and experimental setup. Network elements of the WDM-PON system include: the optical line terminal (OLT), feeder fiber, remote node (RN), distribution fiber, and subscribers. OLTs in the central office (CO), were connected to corresponding WDM-PON links through a fiber distribution panel (FDP). A 1x16 optical switch (insertion loss = 1dB) was employed, to share the S-band supervisory system for different links operating at signal wavelength bands (C/L). The upgrade of the system for the accommodation of more WDM-PON links can be made by replacing the optical switch with one of higher port-number counts. SMFs of 10 km and 20 km were used in link No. 7 and link No. 15, respectively, for the verification of the supervisory system in the real set-up, instead of the full WDM-PON link. For link No. 1, a feeder fiber of 20 km (40 km), and a distribution fiber of 1 km and 10 km (20 km) were used to connect subscribers 4 and 25, respectively. For the downstream transmission, L-band (1573.95nm~1598.75nm) signals modulated in the CO were multiplexed by a 32 channel AWG of 100 GHz spacing (insertion loss = 6~7dB depending on channel number). The multiplexed signals were, then, de-multiplexed with a 1×32 AWG at RN after the feeder fiber, and sent to each subscriber. For the upstream transmission, C-band (1533.40~1558.20nm) DFB lasers were used.

For the generation of the probe pulse (isolated, or coded) in the supervisory system, an S-band tunable laser (wavelength tuning speed for the worst case : from the last (32) to first channel ~ 0.3 second) and a modulated C/S-band semiconductor optical amplifier (SOA) were used in combination, at a wavelength of 1458.15~1481.76 nm, utilizing the cyclic property of the AWG (FSR of ~36nm, 3dB BW of 0.4nm, and maximum integrated crosstalk of ~23dB).
A C-L/S band WDM coupler (C/L→ S isolation of >12dB and S→ C/L isolation of >30dB) was employed in the FDP to couple the probe pulse and multiplexed downstream signals. WDM couplers were also placed after all the distribution fibers, to suppress the out-band crosstalk from probe pulses to subscriber receiver units.

3. Construction of the Surveillance System

3.1 Hardware

Rayleigh backscattered lights from the transmission line when launching the simplex coded probe pulses were fed to the avalanche photo diode (APD) in the OTDR unit. After the decoding procedures on the back-scattered coded traces, a final OTDR trace in a conventional format was obtained [9]. To resolve the added computational complexity from the decoding procedure involving matrix operations (compared to the simple averaging process in a conventional OTDR), a single board computer (SBC) unit was employed with a high-speed interface to the on-board DSP. After the averaging process in the DSP for traces of each corresponding code-word, the averaged coded traces were then sent to an advanced RISC machine (ARM) processor through a dual port random access memory (DPRAM). The traces were then sent to a SBC (using an Ethernet interface) where the decoding operation finally took place.

Figure 2 shows the schematic diagram of the hardware board layout and photographs of the constructed hardware including the case and display unit. The tunable coded-OTDR, power source, the ARM board, C-band TLS (wavelength tuning speed for the worst case: from the last (32) to first channel ~ 0.6 second), single board computer, and a 1x16 optical switch were mounted in the 3.5U case equipped with an LCD monitor, constituting an independent, stand-alone surveillance system. The connection for the surveillance system to the higher hierarchy management system was provided with a USB/Ethernet port along with a PS/2 port placed in the back panel of the system. Also placed in the back panel were the SC/APC output ports of the 1x16 switch, for the connection of WDM PON links. It is worth mentioning that a C-band TLS module was integrated in the board also with a C/S band WDM coupler, to support external sources (such as S-band tunable laser) operating at other surveillance wavelengths.
3.2 Firmware

For the efficient control of constituting hardware units and to provide a reliable transfer of trace data, a systematic command flow was defined before the programming. Under the control of the ARM, the DSP acquires trace data from the ADC. After the DSP reports the completion of measurement, the ARM retrieves the averaged trace from the DSP through the DPRAM, and then sends the write-enable command to the DSP to be ready for the next measurement. To get all the averaged coded traces for the decoding, this procedure was repeated until the reception of trace data for the last codeword. Between the receptions for each of the averaged coded traces, the format conversion of the data (from the TI DSP floating-point format - SMAP II BCD, to the IEEE 754 format of SBC), and the data transfer to SBC were carried out in the ARM processor. Noteworthy, as the matrix multiplication associated with decoding constitutes the major part of the processing time in the SBC, the matrix multiplication operations in the SBC were carried out during the DSP measurement of the next trace, to reduce the idle time.

Fig. 3. Main window of the PC Graphic User Interface

Fig. 4. Control and measurement option windows
3.3 Software

Programming on the SBC was carried out with Visual C++ to support the graphic user interface (GUI) for: the display of the decoded trace, including the event list, control of the measurement options, communication with the ARM board, the decoding option for the received data, control of the TLS, and control of the optical switch.

Figure 3 shows the main window of the constructed software. Position / type of events above the pre-determined threshold values are summarized in the event table below the trace window. Other relevant information – the switch port number, TLS channel number, the measurement distance, the probe pulse width, the averaging time / number, the average loss, and the total return loss of the link, etc., - are also shown in the figure with radio buttons for the control / configuration options. Figure 4 illustrates the measurement configuration window for the selection of: the TLS enable / disable, link number (optical switch port), the probe-pulse wavelength (AWG channel), the pulse-width, the measurement range, the averaging number, and sampling rate. Specification of analysis parameters such as the refractive index, backscatter level, and loss-measurement method also can be made from the same interface. The operation of the OTDR in a conventional averaging mode, or even with other code sets (Simplex, Golay, Bi-orthogonal codes at different code lengths) can be enabled in the OTDR coding option window.

4. Experimental results

![Fig. 5. OTDR traces measured to show multi-port function](image)

Figure 5 shows the measured traces for the link numbers 7 and 15 out of 16 connected links. Selection of the surveillance link was achieved with the command from the SBC to the electronically controlled 1x16 optical switch. The pulse width of the probe pulse was 500 ns. The wavelength was set at 1528.74 nm. It is worth noting again, the extension / upgrade to the WDM-PON system of larger link counts should be easy with the replacement of the optical switches.
Channel 4 and channel 25 of link 1 were used for the demonstration of channel selection. The probe pulse wavelength and SMF link length for channel 4 (25) were 1460.5nm (1476.44nm) and 1km (10km), respectively. It is worth mentioning that the S-band TLS was directly modulated with a sinusoid to reduce the coherent fading noise [12]. With the probe pulse width of 100ns and a peak power of 10dBm, the spatial resolution and accuracy of the measurement was about 10m and 2m, respectively. Figure 6 shows measured loss traces of channels 4 and 25, using the OTDR in a conventional averaging mode (a, b) and in a coded mode (c, d. 31-bit Simplex code, for short-reach application). The averaging number for the OTDR trace, in a conventional single-pulse / 31-bit coded pulse mode, was 3,100 times / 100 times (per each codeword), respectively. Evidently, it can be seen from the figures, a much clearer identification for the distribution fiber after the 10km of feeder fiber was observed with the application of the coding technology. As much as 4.8dB of the SNR enhancement (or 2.4dB in dynamic range) was observed, in excellent agreement with the theoretically predicted values [8-11]. As mentioned earlier, this coding gain also can be used to reduce the required link interrogation time for the measurements at a fixed dynamic range, instead of the trace noise reduction. For example assuming 30km of link length for every user, with 31-bit coded-OTDR it takes about 8 minutes to interrogate all the 512 user lines (excluding pulse guard time. Per user, probing time = 10 μs/km×30 km×3,100 = 0.93 seconds). To compare, for the conventional OTDR it takes about 72 minutes to cover all the 512 users and to achieve the same level of SNR as that of coded OTDR (per user, 10 μs/km×30 km×28,200 = 8.46 seconds).
To investigate the feasibility of including users with long length of distribution fiber, trace acquisition was tested using longer codewords (127 bit, thus better SNR gain = 7.5dB) and higher probe pulse peak power (12.5dBm). Figure 7 compares the OTDR traces of Channel 25 with and without the coding technology. The pulse width of the OTDR pulse was set at 1,000ns to achieve the spatial resolution of 100m. Total of 60km fiber (40km and 20km of SMF, as the feeder and distribution fiber respectively) was used. The averaging number for the OTDR trace in the conventional single-pulse / 127-bit coded pulse mode was 127,000 times / 1,000 times (per each codeword), respectively. As expected, 7.5dB of the SNR enhancement was achieved with the coded OTDR, when compared to the conventional OTDR. Worth to note, as users with such a long span length will be very rare in a conventional access WDM-PON network, we believe that the addition of few users (out of 512 lines) with a long span length (and associated interrogation time) would not cause serious trouble for the total network interrogation time. Successful interrogation of the feeder and distribution fiber of up to 60km was achieved with the long-reach application of the coded OTDR. In contrast, it was difficult to distinguish any event from the trace of distribution fiber with the OTDR in an average mode, due to the high noise level. It is important to mention again, even if this amount of SNR gain in theory can be achieved with the conventional OTDR (with 7.5dB increase in pulse power or orders of magnitude increase in the averaging time), the associated system cost - in the form of signal degradation due to the nonlinearity, or unrealistic interrogation time to cover hundreds of subscriber lines - makes the conventional OTDR inapplicable for our WDM-PON application.

To measure the possible signal degradation from the existence of an in-service probing pulse in the transmission line, the BER measurements have been carried out both for upstream and down-stream data traffic. For the down-stream signal, a tunable laser set at 1593.56nm was used with an external modulator (2.5Gb/s, 2^{23}-1 PRBS, NRZ). For the up-stream transmission, a 1552.52nm DFB laser was used (125Mb/s, 2^{23}-1 PRBS, NRZ). Figure 8 shows the results of measurements: BER curves in a back-to-back condition without OTDR pulses, the BER after 60km of transmission link without OTDR pulses, and the BER after the transmission with OTDR pulses. No transmission penalties in the down/up stream signals from the in-service monitoring were observed (for both the conventional OTDR mode and the coded OTDR mode).
5. Conclusion

We proposed and demonstrated a multi-port, multi-wavelength supervisory system for in-service transmission line monitoring of a bidirectional WDM-PON system. The OTDR technique, based on most up-to-date technologies such as simplex coding, a tunable source, and optical switch, was applied to demonstrate a fast and reliable interrogation of the WDM-PON transmission line up to a 16 port x 32 node (512 user) capacity. Monitoring of individual subscriber’s lines for short-reach and long-reach (total link ~ 60km) nodes were demonstrated without any transmission penalty to the service traffics (2.5Gbps / 125Mbps: down / up). Using the coding technology and high-speed interface, the monitoring time for the whole network was reduced to a reasonable range, which was impossible with conventional technology. We believe that the designed surveillance system would compose a cost and time effective solution for monitoring multiple WDM-PON systems.