Fault-Locating and Supervisory Technique for Multistaged Branched Optical Networks

Yung-Kuang Chen and Sien Chi

Abstract—**A fault-locating and supervisory technique for large multistage branched optical fiber networks is proposed. The requirement of ultra-wide dynamic range of an optical time-domain reflectometer (OTDR) to diagnose the network can be tremendously relaxed. Not only can the failure of optical splitter itself be monitored, but also any faults of the fiber links whether before, after, or between optical splitters can be located. The feasibility of this technique was experimentally demonstrated in a 128-branched network using an erbium-doped fiber-amplifier-enhanced OTDR.**

I. Introduction

THE USE of optical power splitters is steadily increasing in passive branched optical fiber networks, which have been extensively employed in cable TV systems, local area networks, and fiber-to-the-home systems [1]–[3]. Techniques for locating any fiber link faults and for supervising optical splitters become more important after the installation of such distribution networks. For centralized and automated network operation, the use of an optical time domain reflectometer (OTDR) is suitable for fault location from the end of one fiber at a telephone local central office (CO) or a TV headend [3]. However, today's OTDR is unable to diagnose the branched networks due to lack of high spatial resolution with sufficient single-way dynamic range (SDR). Though one fiber failure occurring after a 16-way optical splitter can be detected [4], it is difficult to determine failure length accurately due to the poor resolution ($\simeq$ 100 m) of OTDR's.

In this letter, we propose a hybrid fault-locating and supervisory technique for branched optical fiber networks. The requirement of ultra-high dynamic range combined with high resolution of an OTDR to diagnose a large multistaged N-branched network can be relaxed by the introduction of optical switches and a wavelength-division-multiplexing (WDM) technique. The operation status of each optical splitter is monitored by the detector array. The feasibility of this technique is demonstrated experimentally in a two-staged 128-branched network.

II. Operation Principle and Analysis

The operation principle for the proposed technique is illustrated in Fig. 1. In the CO or headend, an OTDR operating at wavelength λ_1 is passed through the $1:N$ mechanical optical switch and then combined with a transmitted service signal at λ_2 by a WDM coupler to provide in-service testing. Service signals carried by λ_2 were distributed by a $1 \times N$ optical splitter. A fraction (e.g., 2%) of signal power of each output port can be monitored by a detector through a fiber tap, and thus the status of this N-way splitter can be supervised by an N-detector array through a column-wise N-taps as shown in Fig. 1. No signal detected in all output ports implies the complete failure of either this splitter or the fiber link in front of the splitter. The active optical splitters as shown in Fig 1 are used at some front splitter-stages in distribution sector of the network. Each active splitter consists of a WDM demultiplexer, a $1 \times N$ passive splitter, a 1: N optical switch, and N pieces of WDM multiplexers. The passive splitter in each active splitter is supervised by a detector array similarly to that of the CO.

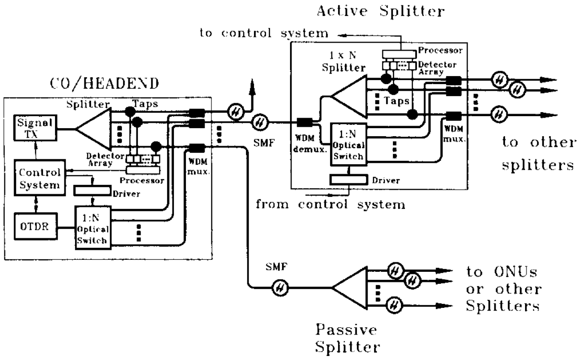

Fig. 1. Proposed fault-locating and supervisory technique for multistaged branched fiber networks.

There are two kinds of supervising operation. Under normal conditions, the service signals are distributed down to all branched customers or optical network units (ONU's) through all splitters. The OTDR is operated in a batch-scanned testing mode to measure the branched network. Batch test results are periodically compared with the stored reference traces, providing early detection of network degradation. By obtaining early indication of an outage, the system dramatically reduces customer downtime. The batch-scanned testing will be stopped while the network control system receiving an alarm notification from whether the monitored detector arrays, the unusual fiber link attenuation found in the batch testing, or an out-of-service report from the customer's call. In such an abnormal condition, all optical switches in CO and in the

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related active splitters will be arranged automatically to the specific optical branching path by the network control system according to both the address of occurring failures and the reference network-links map. The electrical control/monitor signals to/from the network control system can be carried by the copper wires in the same fiber cable.

The arrangements of optical switches combined with the WDM demultiplexers and/or multiplexers in the CO and distribution sector bypass the OTDR signal traveling through the passive splitters and relax the requirement of dynamic range, and thus OTDR can access the fiber links in the rear network remote from the CO. We assume that the $1 \times N$ passive splitters and active splitters are used in the last branching stage and the other stages, respectively, in a multistage branched network. The average fiber link length between two stages is D (km) with attenuation of α (dB/km). Then the total number of branched fibers in which fiber faults can be located is $M = N^s$, where s is the total splitter stages used while the branched network can be diagnosed through the proposed technique using an OTDR with SDR of Q (dB), and $s = k+2$. The k is the maximum number of stages of active splitters; k is an integer and can be described as

$$k \le \frac{Q - \alpha \cdot D - 10\log(N) - (L_{\text{mux}} + L_X + L_N)}{\alpha \cdot D + L_{\text{demux}} + L_{\text{mux}} + L_X}.$$

Here, 10 log (N) and L_N are the splitting and excess losses of the splitter, respectively. L_{mux} and L_{demux} are the insertion loss of the WDM multiplexer and demultiplexer, respectively. L_X is the insertion loss of the $1: N$ mechanical optical switch and is always less than 1.0 dB with back-reflection < -50 dB for switches with N up to 32. Table I shows the fault diagnostic capability of our proposed technique using a high resolution (e.g., 2 m) OTDR with $Q = 15$ dB and 20 dB, respectively, with the following parameter values: $\alpha = 0.25$ dB/km, $D = 2$ km, $L_{\text{mux}} = L_{\text{demux}} = 0.5$ dB, and $L_X = L_N = 1.0$ dB. For example, a three-stage 4096-branched network or a five-stage 32768-branched network can be supervised through this technique using an OTDR with SDR of 20 dB, however, this SDR figure is only capable of diagnosing a single-staged 64-branched network by the conventional technique. Consequently, the total branched fibers being able to be diagnosed through the proposed technique can be increased tremendously as compared with that case using conventional technique.

TABLE I

THE FIBER FAULT DIAGNOSTIC CAPABILITY OF OUR PROPOSED TECHNIQUE COMPARED WITH CONVENTIONAL TECHNIQUE FOR AN OTDR WITH SDR OF 15 AND 20 dB

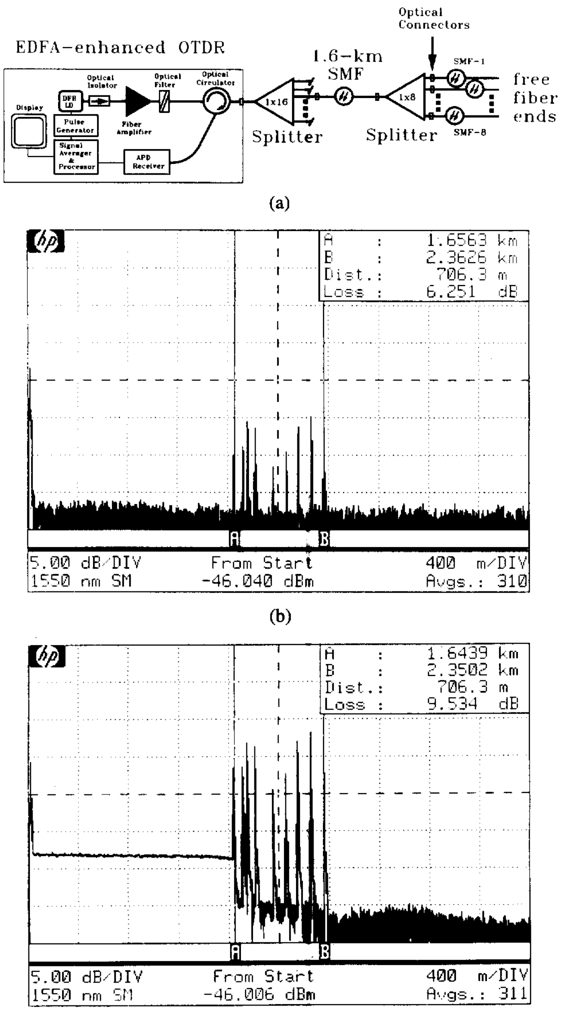
Q / k,s,M / N / Technique		15 dB			20 dB		
		k	s	M	k	s	M
Conventional [4]	N	X	1	16	X	1	64
This Work	16	0	2	256	1	3	4096
	8	1	3	512	3	5	32768

III. EXPERIMENTS AND DISCUSSION

The feasibility of the proposed technique was demonstrated in a simplified two-staged branched single-mode fiber (SMF) network as shown in Fig. 2(a). One output port of the 1 × 16 splitter was connected to a reel of conventional SMF, whereas the other free ports were tightly bent to eliminate any reflections. A reel of 1.6-km long SMF was branched to eight ONU's by a 1 × 8 splitter and followed by 66-, 102-, 164-, 307-, 407-, 503-, 607-, 706-m long SMF's at the output ports #1, #2, $\cdots$, #8 of the splitter, respectively. The typical loss value of the 1×16 and 1×8 splitters including excess loss and connector loss was about 13 dB and 10 dB, respectively. For supervising this 128-branched network, the SDR of an OTDR is required to be more than 24 dB.

In our experiment, an erbium-doped fiber amplifier (EDFA) enhanced OTDR as shown in Fig. 2(a) was used. This OTDR was modified with a 1.549-μm DFB laser diode, a post EDFA followed by an optical interference filter with 2.5 nm passband, and an optical circulator. The EDF length of 7.5 m, pumped by a 1.48-μm laser diode with power of 24 mW, was chosen to both maximize the SDR of OTDR and avoid the detrimental transient gain-compression effect [5] in EDFA. This OTDR has an SDR of 14.5 dB (i.e., an improvement of 11.5 dB over the standard version of HP 8146A OTDR) and an event resolution of 2 m for the 5-ns pulse operation. The Rayleigh backscattered trace of the whole network for about five-min. averaging time is shown in Fig. 2(b). The backscattered reflection signal of the optical connection at the input port of the 1×8 splitter and all Fresnel reflections of the eight-leg fiber ends of this splitter were observed. However, the backscattered trace of the 1.6-km SMF was missed due to insufficient SDR of this OTDR. When the 1 × 16 splitter was bypassed by replacing it with a 2-m long fiber jumper, the OTDR trace of the rest network was shown in Fig. 2(c). The backscattered power distribution along the 1.6-km fiber was no more disappeared. Any fiber faults occurred, whether the reflective breaks or non-reflective faults (resulted from crushed fiber), in the link can be found and events can be identified.

The OTDR trace of the second-staged branched links in Fig. 2(c) can be zoomed horizontally as shown in Fig. 3(a). The detailed information for the splitter itself can be seen as shown in Fig. 3(b) by further zooming the trace around position A in Fig. 3(a). The measured distance (11.3 m) of the splitter itself coincided with the physical length ($\simeq$ 11 m) from the input connector to the output connectors. Similarly, the measured fiber length of each leg of the splitter was identical to the length of each corresponding fiber of eight SMF's. When a fiber break occurs, for example, at the beginning of the sixth leg, then the trace after a two-minute measurement is shown in Fig. 3(c). The Fresnel reflection of the end of the sixth leg disappears and a new Fresnel reflection signal arises at position A. This fiber break can be recognized and accurately located by comparing these two traces. If trace recognition



(a)

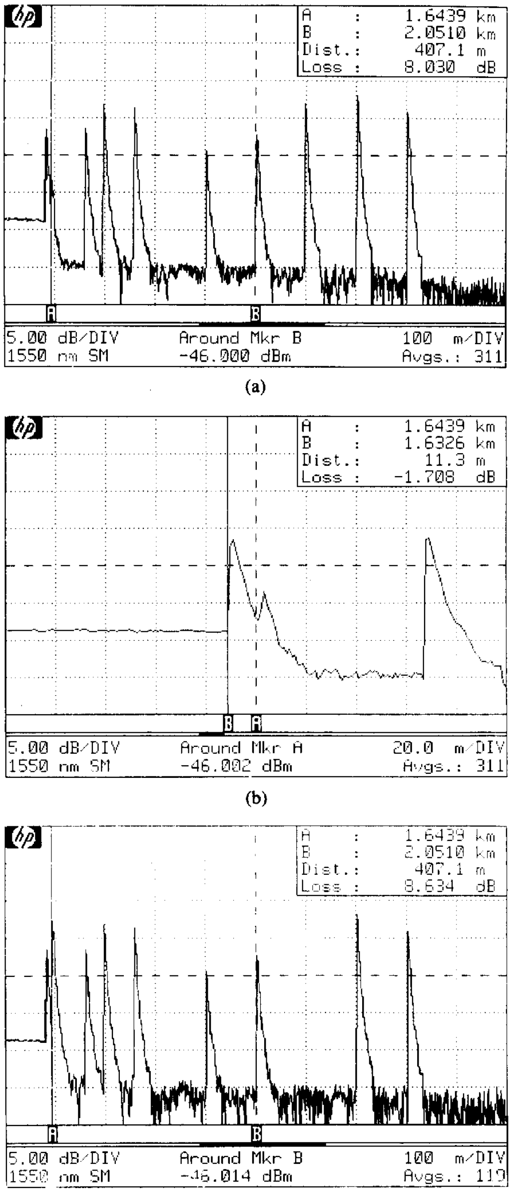
(b)

(c)

Fig. 2. A two-staged 128-branched network: (a) the experimental setup, and the backscattered OTDR traces for (b) the whole network and (c) the rest network when the first-staged splitter was bypassed. Horizontal scale: 400 m/DIVision, Vertical scale: 5 dB/DIV.

and processing techniques are employed, more than one fiber failure (reflective faults) can be identified. On the other hand, the nonreflective faults in branched links of the last splitters are unable to be identified if passive splitters are used in the last splitter-stages. If the active splitters are used, the nonreflective faults in all links can be identified by OTDR while OTDR with sufficient resolution.

Although transmission tests were not carried out in the experiment, this proposed technique will not affect the service-signal transmission performance, i.e., there will be no degradation of the bit-error-rate, if low-loss components with low backreflection (< -40 dB) and high isolation (> 30 dB, to avoid crosstalk) are used, and the problem of multiple reflections between optical connectors is well-controlled. Currently available components (switches, WDM's, taps, and splitters) have demonstrated their excellent characteristics for meeting application requirements for testing branched networks as described here.



(a)

(b)

(c)

Fig. 3. The zoomed OTDR traces (H: 100 m/DIV) of (a) the second-staged branched links, (b) the 1 × 8 optical splitter itself (H: 20 m/DIV), and (c) an fault-occurred branched network (H: 100 m/DIV).

IV. CONCLUSIONS

A fault-locating and supervisory technique for branched fiber networks has been proposed and demonstrated. Not only the failure of optical splitters can be detected, but also any fiber faults in the links whether before, after, or between splitters in multistaged branched network can be located. This technique is suitable for an automated in-service network surveillance system to provide real-time testing, saving the cost of dispatching a technician to perform routine testing and reducing the time taken to identify faults after an outage occurs.

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