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Optimal Matching Approach for Cascaded Encoder in Remote Coding Scheme-based Passive Optical Network Monitoring System

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An optimal matching approach is proposed to maximally ensure the output power uniformity of the cascaded encoder in the passive optical network (PON) monitoring system based on a remote coding scheme. The calculation results show that the optimum arrangement can effectively reduce the difference of the total insertion loss in comparison to the random arrangement (i.e., 0.07 dB vs 2.67 dB in the cascaded encoder with 16 output ports). The proposed approach realizes the optimum configuration for the 1×2 optical splitters used without adding any extra components. The test results of the fabricated cascaded encoder with 32 output ports prove the feasibility of the proposed approach.

Keywords : Link monitoring, Cascaded encoder, Remote coding scheme, PON system
OCIS codes : (060.2340) Fiber optics components; (060.4257) Networks, network survivability; (060.4261) Networks, protection and restoration

I. INTRODUCTION

PONs are generally recognized as the most promising candidate for broadband access systems due to the huge-bandwidth provision, simple maintenance and operation, and easy upgradability [1, 2]. Fiber-to-the-home (FTTH) PONs seem to be the ultimate winning solution for tomorrow's last mile bottleneck. Important FTTH deployments have been carried out in most of the world over the last two decades [3]. However, many FTTH management problems have become increasingly prominent, resulting from the very little information available to the center office (CO) manager about the network. With the increase in demand for reliable service delivery, fast fault detection is critical for reducing provisioning time and improving quality of service (QoS) [4, 5]. For instance, when an optical network unit (ONU) is not communicating with the CO, the manager cannot make a remote diagnosis and determine the cause. Consequently, a truck-roll tour and outside intervention of technicians is required for the troubleshooting. This time consuming and inefficient troubleshooting method usually causes customer dissatisfaction and complaints. Fortunately, PON monitoring provides an effective way to develop a high quality and reliable PON system, which can significantly reduce the operational expense (OPEX) for both the operators and customers [6, 7]. Specifically, a low cost, simple but effective fault monitoring system for fiber-fault identification is essential [8].

Accordingly, the monitoring of the PON fiber plant is required whether for reliability or maintenance purposes. Recently, a variety of optical time domain reflectometry (OTDR)-based and non-OTDR techniques have been proposed for the monitoring of link quality in a PON. OTDR is efficient for monitoring the point-to-point (PTP) network but ineffective in point-to-multipoint (P2MP) networks because the final trace reported by the OTDR represents the linear sum of the power returned from different branches [9, 10]. The modified OTDR techniques aiming to apply

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in P2MP network, such as reference reflector and tunable OTDR, are limited by network size and high-cost OTDR equipment, respectively [4, 7]. For the reference reflector based monitoring technique, an OTDR is located in the CO and the end of each branch is equipped with reflective elements. The presence and height variation of reference reflection peaks at the CO show the branch link status. For a tunable OTDR based monitoring technique, all branches are successively identified by using a tunable OTDR in the CO and a wavelength selective reflector set at the end of each branch. The tunable OTDR can identify each branch link status one by one because all branches contribute to the backscattered signal but only one branch contributes to the end reflection peak. In addition, a mini-OTDR is integrated into each ONU to measure the backreflected and backscattered echoes, which is a so-called embedded OTDR based monitoring technique that has also been presented. The signaling requires intrusion into the data channel, so the data and tests signals can be time-slotted. This, however, not only limits the effective data bandwidth and increases data delay but also requires dedicated transceiver modules, OTDR facilities and space on the optical line terminal (OLT) line card [11].

To overcome the above issues, two typical non-OTDR schemes, periodic coding and optical frequency hopping/periodic coding schemes have been presented. Both schemes place passive encoders at the end of each drop fiber (DF) [12, 13]. The passive encoder consists of fiber Bragg gratings (FBGs) and appropriate length patchcord, which is simple and easy to construct. For these two schemes, a decoding system located at the CO is used to decode the codes coming from the different branches and the status of each branch can be identified. Moreover, a monitoring scheme based on an optical frequency domain reflectometer (OFDR) employs a frequency-modulated continuous-wave signal as the monitoring signal and measures the interference signals created by the interferometer units (IF units). Each IF unit includes only a uniform FBG and a mirror [14, 15]. It is also worth noting that relevant research has been widely performed during the last two decades [6]. In general, research in this topic is motivated basically by both performance of the scheme and overall cost of the monitoring system.

In previous work, the remote coding scheme using cascaded encoder at the remote node (RN) and identical reflector at each ONU was proposed and experimentally demonstrated [16]. For this scheme, multiple power splitter/combiners (PSCs) with cascaded structure replace a single PSC to arrange the corresponding FBGs. The connection of FBGs between two PSCs follows a certain design rule to ensure that the number of FBGs is minimum. However, the random connection between different PSCs used may cause nonuniform power output due to the fabrication error of PSCs. In particular, a fused biconical taper (FBT)-based PSC with steel tube package is given priority for reducing the size of the cascaded encoder. Note that the uniformity performance of planar lightwave circuit (PLC) splitter is better than that of an FBT splitter [17]. Consequently, the nonuniformity may be multiplied by product as the different PSCs are randomly connected. The monitoring signals may suffer from total insertion loss (IL) with a big difference and then increase the difficulty in the final recognition processing. Especially in practical application, it may directly lead to a high false alarm rate (FAR) or even in the entire system not working properly. Hence, the optimal matching approach is necessary to maintain the normal performance of the PON monitoring system.

II. PRINCIPLE AND ANALYSIS

As the key device of the remote coding scheme-based PON monitoring system, the cascaded encoder is constructed by multiple 1 × 2 PSCs with coupling ratio of 50:50 and FBGs with a high reflectance. Note that length of the patchcord of each FBG should be appropriate to control the size of the cascaded encoder. In the actual fabrication process, the length of the pigtail of each FBG is about 20~40 cm for the different stages. The schematic diagram of the cascaded encoder is illustrated in Fig. 1. The

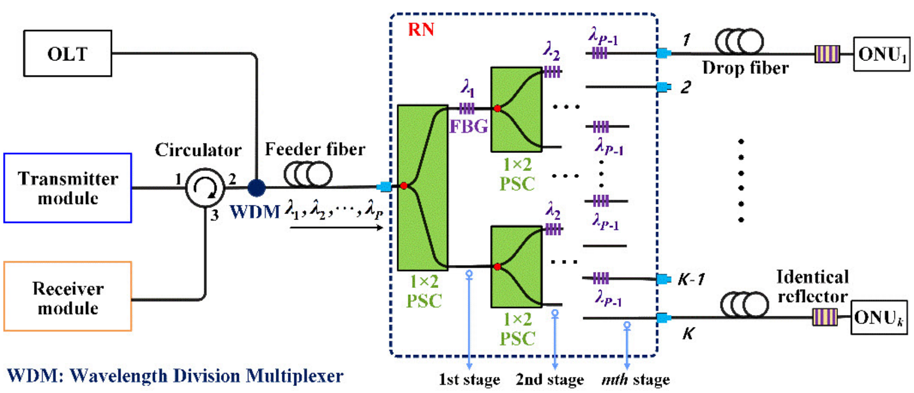


FIG. 1. Schematic diagram of the cascaded encoder in the PON monitoring system based on remote coding scheme. The cascaded encoder at the RN is constructed by multiple 1 × 2 PSCs with coupling ratio of 50:50 and FBGs with a high reflectance.

cascaded encoder replaces the multi-port PSC at the RN in a PON frame, which can simultaneously realize optical splitting and coding. Specifically, the detecting pulse signal containing P ($P = 1, 2, \cdots$) wavelengths is generated by the transmitter module. Then, it is coupled with normal data traffic via wavelength division multiplexer (WDM) and sent into the feeder fiber. At the RN, the cascaded encoder selectively reflects the wavelength components and outputs the unique combination of wavelengths to each ONU. All monitoring signals are reflected by the identical reflector and passed into the receiver module via an optical circulator. Finally, the corresponding signals are sent to the network recognition algorithm to evaluate network status. Status of each DF can be obtained by analyzing the assigned combination of wavelengths.

For a cascaded encoder with K output ports, the number of PSCs used is K-1 and the IL corresponding to each output port roughly equals the case of a single PSC without considering the connection loss. Recall that the random connection of PSCs in the cascaded encoder may cause nonuniform output with big difference due to the fabrication error. Therefore, the optimal matching approach is proposed to ensure the normal operation of the PON monitoring system. In this section, we start with the principle of the proposed approach and then give some analysis.

Figure 2 illustrates the basic flow of the proposed approach. Note that the IL values for two branches of each PSC can be obtained by measurement or product test report. The flow of the proposed approach can be divided into 4 main steps. Firstly, all PSCs are separately numbered and two branches are labelled with IL_1 and IL_2. Secondly, MATLAB program is used to generate all possible combinations. It is worth noting that the calculation process used to generate all possible combinations cannot be simply classified as an exhaustive search approach. When the position of one branch of any PSC is fixed, the other branch is also limited and cannot appear in all positions. Here, two cases need to be considered: 1) Any two numbered PSCs are exchangeable; 2) Two branches in a PSC can also be exchanged. Note that these two cases are independent. Thirdly, when a combination is calculated, the corresponding position of all numbered PSCs and total loss of each output port are recorded. Here, the total loss of each output port is defined as α_i, where i is the number of the corresponding output port. Assume that all combinations generate N sets and each set includes K total loss values. Lastly, total loss values in N sets are respectively calculated and the minimum value of standard deviation (SD) can be obtained. The minimum SD value corresponding to the combination is the optimal match. The calculation of SD in the proposed approach is based on the SD formula and shown in Fig. 2, where $\bar{\alpha}$ is the average of total loss values in each set.

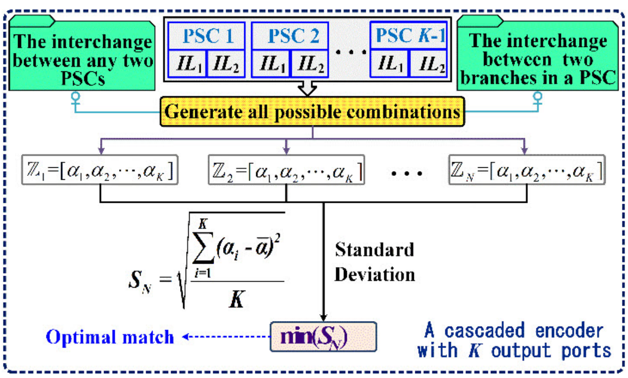


FIG. 2. Flow diagram of the optimal matching approach with 4 main steps. 4 steps include: 1) number of each splitter and its branches; 2) generation of all possible combination; 3) generation of N sets with each set including K total loss values; 4) solution of the minimum SD value for N sets.

In order to better illustrate the basic flow of the proposed approach, we take a cascaded encoder with 16 output ports, for example. Here, 16 output ports instead of 32 output ports are selected to more clearly present the position changes of each splitter and its branches. Then, it seems that the calculation is not consistent with the following experiment. However, the calculation for 16 and 32 output ports is the same in principle. According to the popular specification of 1 × 2 FBT-based PSC, we first generate the corresponding IL values by the simulation, the maximum uniformity of each PSC is less than 0.8 dB [18]. Recall that the IL values can be directly obtained by the product test report. Therefore, values of the product test report can be used as a reference for the IL values generated by the simulation. The related IL values are randomly generated in the range between 3 dB and 3.8 dB, which are listed in Table 1. For simplicity, all FBGs are removed in the following discussion because it has no effect on the output uniformity. Thus, the structure without

TABLE 1. The IL values of the PSCs in the calculation (unit: dB)

PSC1		PSC2		PSC3	
IL_1	IL_2	IL_1	IL_2	IL_1	IL_2
3.28	3.66	3.21	3.49	3.26	3.19
PSC4		**PSC5**		**PSC6**	
IL_1	IL_2	IL_1	IL_2	IL_1	IL_2
3.12	3.05	3.28	3.77	3.17	3.03
PSC7		**PSC8**		**PSC9**	
IL_1	IL_2	IL_1	IL_2	IL_1	IL_2
3.46	3.07	3.16	3.69	3.03	3.41
PSC10		**PSC11**		**PSC12**	
IL_1	IL_2	IL_1	IL_2	IL_1	IL_2
3.67	3.02	3.03	3.03	3.58	3.36
PSC13		**PSC14**		**PSC15**	
IL_1	IL_2	IL_1	IL_2	IL_1	IL_2
3.29	3.72	3.70	3.07	3.15	3.08

FBGs is defined as a simplified cascaded encoder.

Obviously, if the PSCs are randomly connected in the cascaded encoder without considering the connection losses, the maximum and minimum total losses of the corresponding output ports are 14.78 dB and 12.11 dB, respectively. In Fig. 3, the red and blue dotted lines indicate the signal paths that generate the maximum and minimum total losses, respectively. The difference between the two output ports is 2.67 dB. Due to the round trip of the monitoring signal through the network, the difference is double. More importantly, the difference introduced by the cascaded encoder may increase the difficulty in final recognition processing. That is, a big difference between reflected pulses causes trouble in the definition of the threshold function,

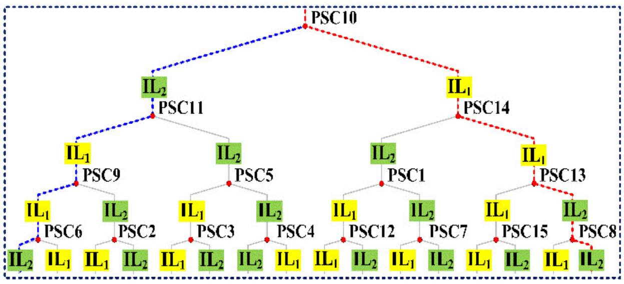
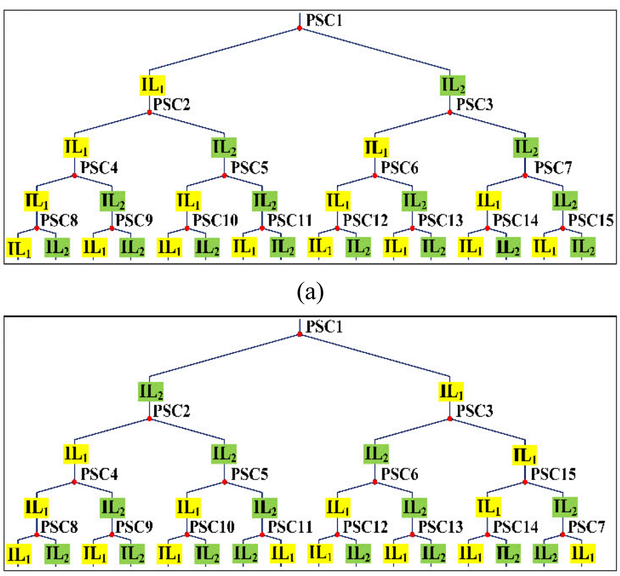


FIG. 3. The signal paths for the maximum and minimum total insert losses in a simplified 16-port cascaded encoder with a full binary tree structure. Blue and red dashed lines indicate maximum and minimum total loss paths, respectively.



(a)

(b)

FIG. 4. Two arrangements corresponding to the PSCs used in the simplified 16-port cascaded encoder in a full structure: (a) numbered arrangement, all PSCs follows the numbering principle from top to bottom, left to right; (b) optimum arrangement, the corresponding PSCs and the branches exchange the position.

especially in a PON with equidistance. Note that the difference of total loss between different output ports may be greater with the increase of the output ports number.

As the basic components of the cascaded encoder, the specification of PSCs largely depends on the fabrication technology. The fabrication error seems to be unavoidable due to uncontrollable factors in the production process. However, the error caused by the fabrication technology can be compensated by the optimum arrangement of the PSCs used for the cascaded encoder. Note that the proposed approach using the optimum arrangement of the PSCs used cannot ensure absolutely uniform output of each output port. However, the proposed approach realizes the optimum configuration based on the PSCs used to make all power outputs maximally uniform. More specifically, 15 PSCs used in the cascaded encoder with 16 output ports are sequentially numbered in a full binary tree structure, and branches located in the same side are labelled with the same identifications (i.e., the subscript of IL with 1 and 2), as shown in Fig. 4(a). Then, the optimal match can be obtained by 2 steps: 1) Two branches of PSC1, PSC3, PSC7 and PSC11 simultaneously switch positions in the same PSC; 2) PSC7 and PSC15 exchange positions with each other. After the above steps, the minimum value of the SDs is 0.1592. The optimum arrangement of the PSCs used in a cascaded encoder with 16 output ports is shown in Fig. 4(b). Note that the optimum arrangement may not be unique for the minimum SD value. For example, PSC5, PSC6 and PSC12 perform the first step, PSC7 and PSC15 do the second, and the SD value is also 0.1592.

Here, we can also calculate the total losses between different output ports after the proposed approach has been applied in the fabrication of the cascaded encoder with 16 output ports. Recall that the difference of total losses between the first and last output ports is 2.67 dB as the PSCs used are randomly connected. By contrast, the difference between the same ports is only 0.07 dB after using the optimum arrangement. Obviously, the proposed approach can effectively improve the uniformity performance of the output ports. In a PON with cascaded architecture, the proposed approach may also be used to uniformly split the downstream signal by power division to each DF. In addition, we can also do another extended discussion for a modified optimal matching approach, which makes the power of reflected monitoring signals to keep uniform. It may be suitable for a PON with multiple equidistance. That is, the total losses corresponding to each output port are configured according to the different fiber link losses with round trip. However, the values of each fiber link loss must be known in advance.

III. VERIFICATION AND RESULTS

In this section, we prove the feasibility of the proposed approach by fabricating a cascaded encoder for a practical

PON monitoring system based on remote coding scheme. Commonly, the typical split ratio of Ethernet passive optical network (EPON) is 1:32. Therefore, the fabricated cascaded encoder based on the proposed approach is designed with 32 output ports for the remote coding scheme-based PON monitoring system. The photo of the fabricated cascaded encoder with 32 output ports is shown in Fig. 5. The input and output ports of the cascaded encoder use FC/APC connectors. Here, the specification of 31 PSCs used in the cascaded encoder with 32 output ports is similar in Ref. [18]. Based on the proposed approach, 31 PSCs are connected with corresponding FBGs and then enclosed in a 1U chassis. For the cascaded encoder, the components include multiple 1 × 2 PSCs and FBGs. The pigtails of these components are bare fibers. All connections are made through fiber-optic fusion instead of a connector. Fiber fusion not only minimizes losses, but also suppresses bending losses caused by connectors. Note that the welding loss of the two bare fibers can be easily controlled within 0.01 dB. For a 1 × 2 PSC, the IL value is not less than 3 dB. Compared with the IL, the welding loss can be negligible. Therefore, the coupling losses between different components are not considered in the calculation model.

For the verification, 32 output ports are measured separately and the test results are shown in Fig. 6. The output power for each output port is measured by a standard optical power meter as a fixed continuous-wave broadband light source with output power of 10 dBm is given in the input port. All output power falls within the range between -7.56 dBm and -7.12 dBm, indicating that the difference between any two output ports is less than 0.5 dB in the actual measurement.

FIG. 5. The photo of the fabricated 32-port cascaded encoder enclosed in 1U chassis with FC/APC connectors. 1 input port and 32 output ports can directly connect the DF link with FC/APC.

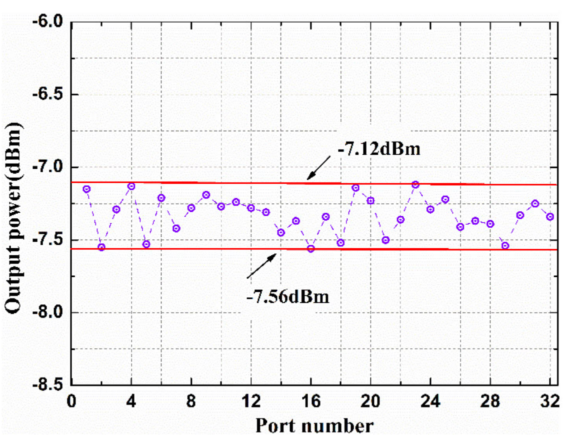


FIG. 6. Test results for output power corresponding to each port. The output power for 32 output ports falls within the range between -7.56 dBm and -7.12 dBm.

IV. CONCLUSION

We have proposed an optimal matching approach for the cascaded encoder of the PON monitoring system based on remote coding scheme. The calculation results show the proposed approach can effectively improve the performance of the output uniformity between all output ports. The test results of the fabricated cascaded encoder with 32 output ports prove the feasibility of the proposed approach. The uniform output performance of the cascaded encoder ensures that the PON monitoring system works smoothly, which can promote the deployment of the PON monitoring system based on remote coding scheme in practical applications.

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