Study of passive optical network monitoring based on non-OTDR*

LI Chuan-qi (李传起), WANG Da-chi (王大迟), and HU Jin-lin (胡金林)**
College of Electronic Engineering, Guangxi Normal University, Guilin 541004, China

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Aiming at the defects of passive optical network (PON) monitoring based on optical time domain reflectometry (OTDR) technology, we research the non-OTDR monitoring technology. The coding scheme based on periodic encoder monitoring is discussed, and its limitation is analyzed. On this basis, the monitoring technology based on optical code division multiple access (OCDMA) is put forward. We analyze the feasibility of monitoring scheme based on PON of OCDMA, design a monitoring plan, and then use OptiSystem to simulate the design. The results of simulation and bit error rate (BER) analysis show that this monitoring technology can overcome the deficiencies of OTDR and distinguish the monitoring signals of different fiber branches clearly, which meets the demands for high beam split ratio of multi-user communication.

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In recent years, with unique advantages of broadband networking, passive optical network (PON) has become a mainstream form of broadband access network. With increasing number of PON users, once the fiber optical network fails to work, it will cause great economic losses to operators and users, so the real-time monitoring is particularly important for PON lines. Now commonly used tool in optical fiber monitoring is the optical time domain reflectometry (OTDR). By analyzing Rayleigh scattering and Fresnel reflection generated in the process of signal transmission in the fiber link, we can achieve an effective fiber link monitoring. But in one-to-many PON, the monitoring signal received by OTDR is the superposition of many branch fibers, that is to say, signal of each branch fiber can not be effectively monitored. At present, many PON monitoring methods based on OTDR have been put forward, such as OTDR monitoring technology of single wavelength[1-4], tunable OTDR monitoring technique[5,6] and Brillouin OTDR (BOTDR)[7-10] monitoring technology. But the research of PON monitoring technology based on non-OTDR[11-13] is still not enough.

The technical scheme of OTDR is mostly the redesign of the monitoring light source and the fiber link, so the performance of OTDR is often determined by whether the PON monitoring scheme useful or not, which has some limitations. In this paper, we propose a non-OTDR monitoring scheme, and analyze its performance.

Habib Fathallah et al[14,15] proposed a periodic encoding PON monitoring technology. The PON monitoring scheme is shown in Fig.1(a). A U-band extremely narrow pulse, which is sent from the monitoring system, is transmitted through the PON downlink to the remote node (RN) and split into N subpulses. The subpulse in each optical fiber branch is encoded and reflected by coding mirror (CM) in the front of optical network unit (ONU) as the encoded signal to a monitoring system. We analyze the PON communication status of each branch according to the encoded signal reflected back to the monitoring system. If the communication status of each branch is in good condition, the encoded signal peak of each branch can be displayed on the monitor end. And there is no encoded signal peak of the branch when the communication status is in bad condition. This monitoring program monitors the PON through receiving the encoding peak of monitoring pulse signal.

The key element of the PON monitoring technology lies in the structure of user's CM[15]. The CM is made up of two fiber Bragg gratings (FBGs) as shown in Fig.1(b). The center wavelength of the two FBGs and the wavelength of monitoring pulse are the same, but the reflectivities of FBG1 and FBG2 satisfy the relation of $R_1<R_2=1$. So a light hole is formed between the two gratings, and the code of monitoring pulse generated in the hole is called as multilevel periodic code (ML-PC). The only difference of optical branches is CM length, so the encoded signals of different branches[15] which are determined by CM length should be distinguished.

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** E-mail: lcq@mailbox.gxnu.edu.cn

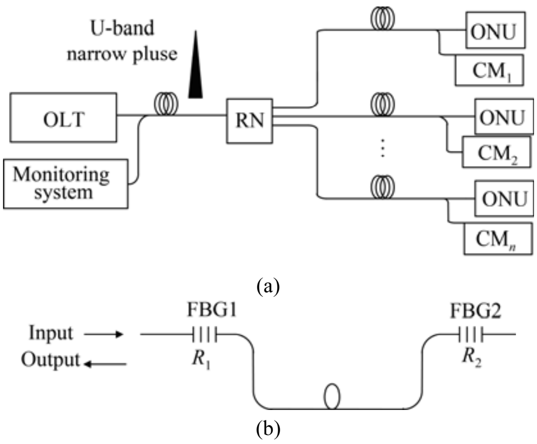


Fig.1 Schematic diagrams of (a) PON monitoring based on periodic encoder and (b) CM structure

We use OptiSystem7 software to simulate the monitor program with four users. The simulation parameters are set as follows. The light bandwidth is 100 MHz, the power is 10 dBm, the noise dynamic range is 3 dB, the gain of erbium doped fiber amplifier (EDFA) is 100, the fiber length is 20 km, the fiber attenuation is 0.3 dB/m, and the splitting ratio is set as 6 dB (4 users) to send monitoring pulse with width of 10 ns. The reflectivity of FBG1 is R_1=0.38, and the reflectivity of FBG2 is R_2=1, then the first six pulses can reflect 99% of the monitoring power. The transmission time interval is 20 ns. The simulation result of signal filtered by the CO and received by the photoelectric detector is shown in Fig.2.

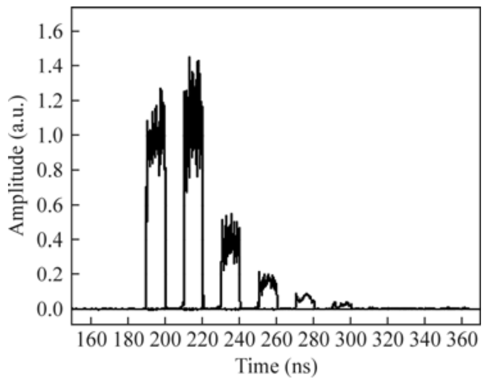


Fig.2 The simulation result of periodic encoders

Using the signal-to-noise ratio (SNR) formula[15] as

$$SNR = \frac{\sigma^2_{\text{SIG}}}{\sigma^2_{\text{TH}} + \sigma^2_{\text{D}} + \sigma^2_{\text{SH}} + \sigma^2_{\text{BN}}} , \quad (1)$$

where σ^2_{SIG} is the useful signal power, σ^2_{TH} is the thermal noise, σ^2_{D} is the dark current noise power, σ^2_{SH} is the shot noise, and σ^2_{BN} is the beat noise, we can obtain the relationship between the number of users and SNR. When there are 64 users, SNR is 10.6 dB, and when there are 128 users, SNR is 5 dB.

From Fig.2 we can draw the conclusions as follows. Starting from the first two pulses, the coded pulse power decays exponentially. The distance between the two FBGs determines the time interval between the two pulses, which is a unique identifier to distinguish the pulses in different branches. Starting from the third pulse signal, the pulse power reduces obviously. The increasing number of PON users, the loss of PON link and fiber, and some other reasons can cause serious interference to PON monitoring results. Such as, if the received coding signal power is too low, the receiver can not accurately obtain fiber branch communication condition, and can not effectively distinguish pulses in different branches, thus resulting in failure of fiber branches, and also the fiber branch can not be monitored timely and effectively.

In order to overcome the defects of periodic coding, we put forward a kind of PON monitoring method based on optical code division multiple access (OCDMA). OCDMA network structure is shown in Fig.3[6]. At the sender end, each road user is assigned an address code, and the different code patterns represent their different addresses. Use the optical encoder for coding user's data. The coded signals of users are superimposed by a star coupler, and then the superimposed signal is transmitted to the receiving end through the fiber. At the receiving end, if the optical decoder and encoder match with each other, the decoding signal has high intensity auto-correlation peak.

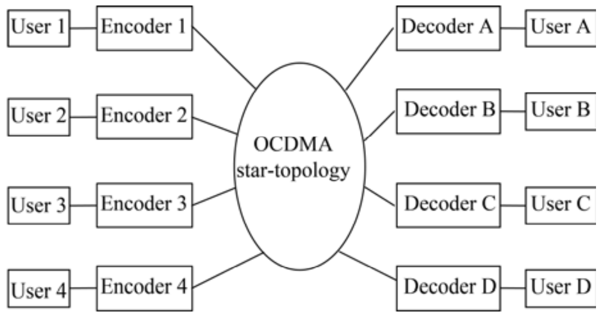


Fig.3 Schematic diagram of OCDMA network topology structure

The PON monitoring program based on OCDMA is shown in Fig.4. We can see that the monitoring data sequence is sent in the CO terminal and is put into PON unit. In the optical splitter, the monitoring data is divided into N sub-branches, which are sent to encoder for encoding in the front of the ONU. Finally, an encoded monitoring signal unlinked via the circulator gets back to the CO end of the monitoring system. Coded signal is decoded with the matched decoder through the optical switch, and it will get a high intensity auto-correlation peak when it is decoded rightly.

By means of analyzing the peak value of auto-correlation, we can obtain the status information of branch. The decline or disappearance of auto-correlation peak power of decoded signal indicates that the branch losses can be serious or even broken, while the disappearance of all the auto-correlation peaks suggests that the fault occurs in the primary fiber rode.

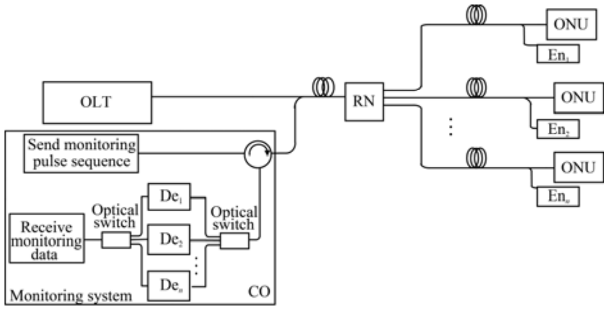


Fig.4 Schematic diagram of PON monitoring based on OCDMA system

The key to this monitoring program is the design of codecs and address codes. The performance of the codec determines the reliability of OCDMA system. The commonly used codecs are fiber optic delay lines, FBGs, arrayed waveguide grating (AWG) and so on. The used address codes currently are prime code, optical orthogonal code, two-dimensional prime code and two-dimensional optical orthogonal code (2D-OOC). Since two-dimensional address codes can accommodate more users, and its code word has excellent performance, this paper chooses this 2D-OOC to verify.

2D-OOC code word parameters can be expressed as (N×L, ω, λ_a, λ_c), where N represents the number of wavelength plates, L is the code word length, ω is the code word by weight, λ_a is the auto-correlation limit, and λ_c is the cross-correlation limit. The codec used for the simulation is FBG, and the address codes are set as (31 31,3,1,1) of {(17,10) (21,11) (26,17)}, {(18,10) (22,11) (27,17)}, {(19,10) (23,11) (28,17)} and {(20,10) (24,11) (29,17)}. We can divide the wavelengths in the range of 1530–1560 nm into 31 equal portions, so the adjacent wavelength tolerance is 1 nm, i.e., the central wavelengths of each wavelength plate are λ_1=1530 nm, λ_2=1531 nm,⋯, λ_n=1561 nm. Each time slice interval is 1 ns.

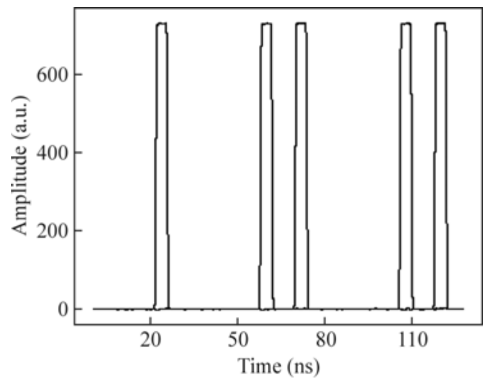
In OptiSystem 7 software, set the simulation parameters as follows. The transmission data is 100000000100 with rate of 250 Mbit/s, the light source bandwidth is 10 MHz, the power is 10 dBm, the noise dynamic range is 3 dB, the gain of EDFA is 100, the fiber length is 20 km, the fiber attenuation is 0.3 dB/m, the splitting ratio is 6 dB (4 users), and FBG reflectivity is R=0.99 which is arranged to monitor the PON OCDMA lines as shown in Fig.4.

The simulation results are shown in Fig.5. Fig.5(a) shows the correctly decoded signals of user 1, whose signal auto-correlation peak is visible after decoding the signal. Fig.5(b) shows the signal of user 1 decoded by the decoder of user 2. The signal can not be correctly decoded, and we can not distinguish the monitoring information.

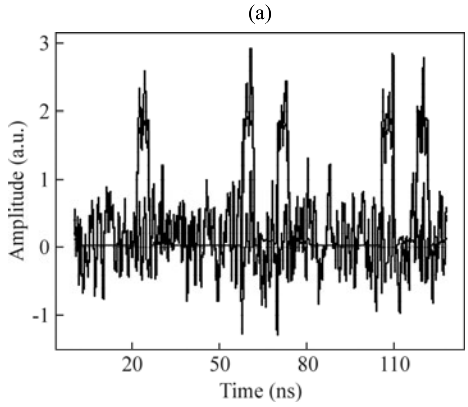
The bit error rate (BER) of 2D-OOC for OCDMA system is caused by the multiple access interference, which can be expressed as[16]

$$BER=\frac{1}{2}\sum_{i=Th}^{K-1}\left(\frac{(K-1)!}{i!\left(K-1-i\right)!}\right)\left(\frac{w^2}{2L^2}\right)^i\left(1-\frac{w^2}{2L^2}\right)^{K-1-i}, \quad (2)$$

where K is the number of actual users, Th is the receiver decision threshold, w is code weight, and L is the code length. Fig.6 shows the system BER versus the number of concurrent users for the 2D-OOC codes of (31 31,3,1), (57 57,8,1), (73 73,9,1) and (111 111,11,1). As can be seen from Fig.6, with the code length and code weight increasing, the BER performance meets the requirement, and the concurrent user capacity of the system grows rapidly. The transmission distance of the OCDMA system used for monitoring is not long, so if the required data transmission rate for monitoring is not too high, the error rate caused by the fiber dispersion is small.



(a)



(b)

Fig.5 Monitoring signals after (a) correctly decoding and (b) incorrectly decoding

We can restore the monitoring data by converting the decoded optical signals into the electrical signals through photoelectric converter after correlation processing, so that there is no need of expensive and bulky optical modules. The data processing module is shown in Fig.7. Analog circuit mainly aims at the correlation processing of photoelectric conversion signal, i.e., signal filtering and amplification, to meet the requirements of analog-to-digital conversion (ADC) device.

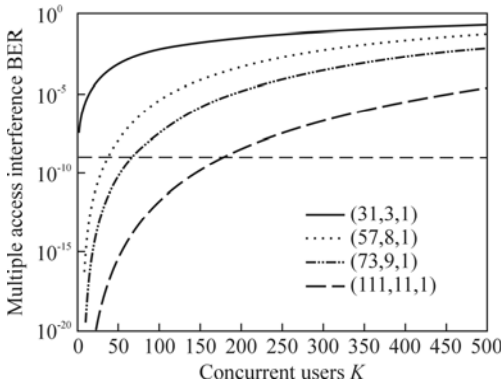


Fig.6 Relationship between BER and the number of concurrent users for different 2D-OOC codes

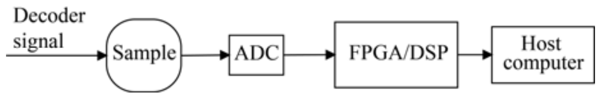


Fig.7 Schematic diagram of the data processing module

Due to the monitoring data rate is in the range of tens to hundreds of megabytes, the corresponding rate sampling devices on the market are quite mature. In the range of the hundred megahertz sampling, ADC module can provide relatively high precision conversion. By the delivery of collected data to the PC, PON real-time monitoring can be realized.

In this paper, the PON monitoring system based on OCDMA is put forward. It has no special requirement on the light source, and its coding deployment is as simple as a series of encoders in the ONU side, while decoder and monitor on the CO side. It can distinguish the monitoring signals of different fiber branches more obviously, realize the real-time monitoring of fiber branch, and improve the efficiency of PON link monitoring. Lastly, it reduces the system maintenance costs by using a data processing module.

In OCDMA system, code word affects the SNR, BER and user capacity, and determines the stability and reliability of the PON monitoring system. Such as, the SAC code can theoretically eliminate multiple access interference, thereby BER is reduced and user capacity is increased. So the research on the performance of code word is the key to the PON monitoring method based on OCDMA.

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