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Experimental demonstration of the real-time online fault monitoring technique for chaos-based passive optical networks

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ABSTRACT

In this paper, a real-time online fault monitoring technique for chaos-based passive optical networks (PONs) is proposed and experimentally demonstrated. The fault monitoring is performed by the chaotic communication signal. The proof-of-concept experiments are demonstrated for two PON structures, i.e., wavelength-division-multiplexing (WDM) PON and Ethernet PON (EPON), respectively. For WDM PON, two monitoring approaches are investigated, one deploying a chaotic optical time domain reflectometry (OTDR) for each transmitter, and the other using only one tunable chaotic OTDR. The experimental results show that the faults at beyond 20 km from the OLT can be detected and located. The spatial resolution of the tunable chaotic OTDR is an order of magnitude of centimeter. Meanwhile, the monitoring process can operate in parallel with the chaotic optical secure communications. The proposed technique has benefits of real-time, online, precise fault location, and simple realization, which will significantly reduce the cost of operation, administration and maintenance (OAM) of PON.

1. Introduction

It is well known that if the important message on communication networks is stolen, attacked and destroyed, tremendous loss will be made to individuals, enterprises, government and even national defense. The current optical communication networks are based on the electrical time division multiplexing (TDM) and optical wavelength division multiplexing (WDM). While the on-off keying modulation format is employed at the optical layer, there is no security at all, since the simple power detection can recognize the data [1–3]. For this reason, chaotic light secure communication technique has attracted considerable attention, because it can be simply realized and allows both real-time and broadband encryption at the physical layer. Up to now, many simulation and experimental results are reported in the aspect of long-haul transmission and wavelength division multiplexing, etc. [4–14]. Nowadays, optical fibers are substituting the copper cables progressively in the access network area, which brings a worldwide acceleration of the passive optical networks (PON) [15]. As a result, secure communication in PON is a fast emerging topic. Recently, the application of chaotic light in PON has attracted great attention [16].

Besides the information security, the fault monitoring is another crucial issue for the quality of service (QoS). According to Ref. [17–19], the monitoring system should be simple, cost-effective, non-invasive to data traffic and compatible with different PON topologies. Several real-time online fault monitoring systems have been reported, with traditional optical time domain reflector (OTDR) assisted by other devices or mechanisms, e. g., fiber Bragg grating (FBG) [20], high-pass filter [21], optical encoders [22], or the Brillouin frequency shift generated in the branch fibers [23]. Although they comply with some of the requirements, they remain complex and costly. Meanwhile, the spatial resolution is low [17]. Thus, it is necessary to develop a real-time online fault monitoring technique which is simple, practical and cost-efficient to reduce the expenditure of operation, administration and maintenance (OAM) for the security-enhanced optical access network.

In this paper, for the chaos encrypted PON, a real-time online fault monitoring technique utilizing the chaotic communication signal is proposed and experimentally demonstrated. The implementation of this technique in WDM-PON is firstly investigated. Two fault monitoring approaches, one deploying a chaotic OTDR (COTDR) to each transmitter, and the other using only one tunable COTDR, are proposed. The performance of both fault monitoring approaches is analyzed in detail. Then, the application of the proposed technique in EPON is investigated.

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2. Demonstration of chaotic light secure communication and real-time online fiber fault detection and location in WDM-PON

WDM-PON is a promising candidate for the next generation optical access network, owing to the capability of providing a higher capacity and a lower cost [24]. In WDM-PON, each ONU uses a unique wavelength to communicate with the OLT. Thus, to ensure the message security of WDM-PON, each channel is encrypted by the chaotic carrier at the corresponding wavelength. The principle system architecture is shown in Fig. 1. The optical line terminal (OLT) is composed of chaotic transmitters emitting the encrypted messages at different wavelengths and a COTDR. The OLT is connected to the remote node (RN) via standard single-mode fiber (SSMF, G. 652). A wavelength division demultiplexer is installed at the RN. Each optical network unit (ONU) contains a chaotic receiver to recover the message through chaos synchronization. For real-time online fault monitoring in chaos encrypted WDM-PON, a COTDR is deployed to each wavelength channel. Alternatively, a tunable COTDR can be placed at the OLT to scan each wavelength channel.

2.1. Experimental system with one COTDR for each wavelength channel

Fig. 2 depicts the architecture of the experimental system. The channel of wavelength λ_1 is taken as an example to demonstrate the composition and principle of the system. In the OLT, the chaotic carrier is generated through optical feedback [25]. The generated chaotic light carrier is launched from the other port of OC_1. Then, the message is encrypted by the modulator through chaos modulation [26]. In our experiment, the message is a non-return-to-zero (NRZ) pseudorandom bit sequence (PRBS) with $2^{15}–1$ length generated by a pulse pattern generator. The modulation depth is set to be 0.3. The EDFA is utilized to compensate the loss of the modulator. The composite signal is divided into two parts by a 90:10 OC_2. One part (90%) of the signal is used for the chaotic light secure communication. The other part (10%) acts as the reference signal of COTDR for fault monitoring. The COTDR consists of OC_2, CIR_2, two 20 GHz photodiodes PD_1 and PD_2, and a correlator. At the subscriber side, the ONU1 consists of OC_3, LD_{R1}, CIR_3, PD_3 and PD_4. The received composite signal is divided into two parts by a 50:50 optical coupler OC_3. One part of the signal is injected into the receiver laser LD_{R1} to regenerate the chaotic light carrier. The injection strength is adjusted by VOA_5. In the other path, the variable delay line (VDL) is utilized to compensate the delay time between the two paths. The length of the VDL is about 7.2 m in our system. Then, the composite signal and the locally generated chaotic carrier are detected by PD_3 and PD_4, respectively. The output electrical signals are launched into a digital storage oscillator to observe the signals in real-time and recover the message m1′. Other wavelength channels are similar to this channel. In this experiment, the WDM system is composed of 8 wavelengths, in which the $\lambda_1 \sim \lambda_8$ correspond to the wavelength channel CH27 ~ CH34 of ITU-T G.692, respectively. The fiber link is 22.54 km standard single-mode fiber (SSMF, G.652).

Firstly, the secure communication is investigated. Two wavelength channels, CH28 (1554.94 nm) and CH31 (1552.52 nm) are used for demonstration. Fig. 3(a) and (b) are the transmission results of CH28 (1554.94 nm) and CH31 (1552.52 nm), respectively. The green (middle), yellow (bottom), and blue (top) time series correspond to the composite signal from the OLT, the regenerated chaotic light carrier at the ONU, and the recovered message, respectively. As can be seen from Fig. 3, when there is no fault in the fiber link, the ONU can regenerate the chaotic carrier based on chaos synchronization, thus the message can be successfully recovered. The calculated Q-factors of CH28 and CH31 are 2.09 and 2.10, respectively. According to relationship between Q-factor and the bit-error rate (BER) [8], the BER of the two channels are both approximately 1×10^{-2}. When the forward error correction (FEC) technique is employed, the BER can reach up to 1×10^{-13}, which can meet the requirement of the optical communications [11,27].

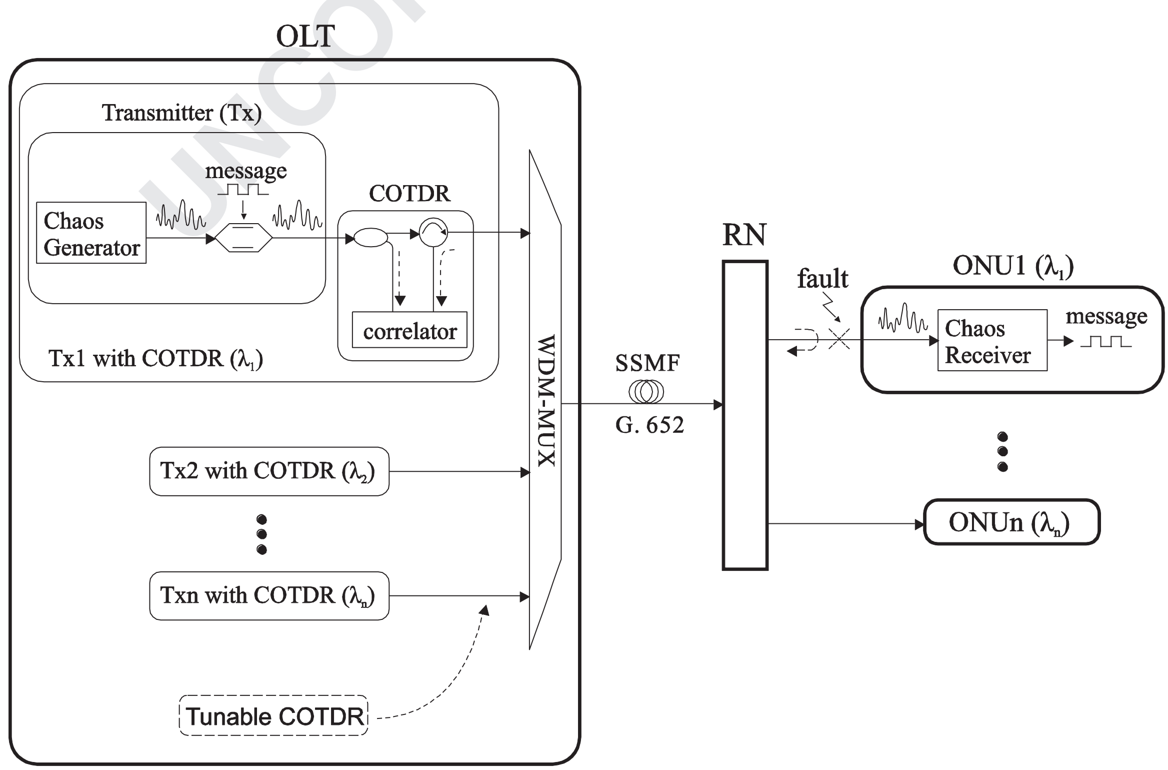

Fig. 1. System architecture of the proposed fault monitoring technique.

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