Fiber Ring Encoder for PON Fault Monitoring

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Abstract

This paper proposes a novel periodic optical encoder for centralized fault monitoring of fiber-to-the home (FTTH) passive optical networks (PONs). The encoder exploits a fiber ring to produce a periodic code. This reduces the cost of monitoring system while maintains good performance and high capacity. We evaluate the performance of this encoding system in terms of signal to noise ratio (SNR). We obtain an SNR of 12.5 dB for a 32 customers network in one shot measurement. We also show that capacity of 64, 128 and 256 could be accommodated in expense of larger but acceptable measurement time.

I. Introduction

Fiber to the home (FTTH) promises a major role in alleviating the last mile bottleneck in the next generation broadband access networks. It provides the ideal medium for streaming video, photo and file sharing applications, on-line multi-player gaming and next generation home networks involving multiple computers and high bandwidth multimedia devices. However, despite its advantages, a typical FTTH passive optical network (PON) with point to multipoint (P2MP) architecture does not have full monitoring capability. Fiber fault monitoring of PONs can save a considerable amount of operational cost. It is found that more than one-third of service disruptions are due to fiber cable problems according to the cases reported to the Federal Communication Commission (FCC) [1].

Most monitoring systems used for fault detection employ optical time domain reflectometer (OTDR) [2]. In a P2MP PON topology, fiber fault detection by OTDR is not possible because the Rayleigh back-scattered light from different branches cannot be distinguished at the OTDR. Several methods have been proposed to overcome this problem [3-6]. Most of these solutions are impractical mainly because their capacity is limited to few customers.

One of the operational requirements for the next generation PON (NG-PON) is optical distribution network (ODN) monitoring and Checking [7]. It is desirable that such monitoring and checking be available regardless of the optical network terminal (ONT) is in service or even not connected. This cannot be achieved with using decentralized monitoring approach where active devices are placed inside the ONTs that measure the performance and then report to the CO.

In [8], an optical encoder was proposed for the first time to be used in an optical centralized monitoring system. In this system, no active components are placed in the field between the customer and the CO and no intelligent modules are embedded inside the customer's ONT. Some practical encoders have been proposed in [9-10] for fault monitoring which increases the capacity while maintaining a relatively low cost.

In this paper, we propose a new coding scheme which is well adapted to the FTTH–PON centralized monitoring system shown in Figure 1. Our encoder further reduces the overall cost of the monitoring system by developing simpler and lower cost optical coding devices (one ring of fiber and one simple 100% reflective Bragg grating). Note that optical rings and micro rings recently become very popular as enabling technology for the development of filters, multiplexers, switching and channel dropping applications [11]. Compared to that of [9] where two gratings are required with two different reflectivities, this

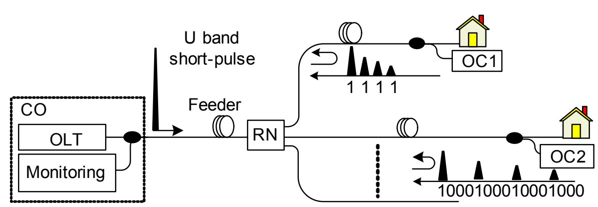

Figure 1. Optical coding monitoring system.

The authors acknowledge the contribution of the Research Center of the College of Engineering, KSU.

978-0-7695-4041-2/10 $26.00 © 2010 IEEE
DOI 10.1109/CNSR.2010.67

encoder replaces one of the gratings by a 2x2 coupler, hence further decreasing the encoder cost. Recall that the PON market is very cost-sensitive, particularly for network elements not shared between customers, i.e. ONTs, distribution and drop fibers (DDFs), and passive coding devices for monitoring of each DDF. Our results show that our new proposal supports the monitoring of a 32 PON customers with SNR>10 dB in only one shot measurement.

One technique to reduce the effect of the noise and hence increase the capacity of the monitoring system in expense of larger measurement time is noise averaging. In noise averaging, we retransmit the monitoring signal many times and average the obtained results. By noise averaging, i.e. repetitive measurements, our monitoring system can increase its capacity to be matched to higher capacity of 64, 128 and 256.

In section II, we introduce the monitoring system and the monitoring process. In section III, we describe the design issues of our ring based device and its operation. In section IV, we show the performance evaluation of the system.

II. Monitoring system

Figure 1 shows an optical system where a U band short pulse with peak power P_s and duration T_s is transmitted downstream from the CO in the U band (1625-1675 nm) reserved for monitoring. This pulse is split into N subpulses at the remote node (RN) using passive splitter, distributed through the DFFs to all ONTs. Each pulse close to the ONT$_i$ ($i=1, 2, \ldots, N$) is encoded and reflected back to the CO by the respective optical encoders OC$_i$.

Each DDF drop is terminated by an encoder that generates a unique code and is located physically close to the ONT. Information on individual DDFs at the CO is discernible due to the fact that each encoder generates a unique orthogonal code.

At the CO, the received signal which is the sum of the DDF codes is decoded to determine the status of the DFF of each customer. The decoding process takes place during a specific time interval called the observation time. Without loss of generality, we assume that the receiver knows the exact observation interval for the desired customer. Indeed, the synchronization is not a part of our analysis in this paper. If the specific DDF is healthy, the monitoring code of the specific customer will be decoded and an autocorrelation peak is then identified. If a break occurs in any DDF, its code will not arrive to its specific decoder and then no autocorrelation is observed at the decoder output in the CO.

III. Encoder design

A single incident pulse generates a code composed of w multilevel pulses that are equally spaced with a spacing p. Each customer has a Bragg grating with 100% reflectivity and a ring of fiber with length L as shown in Figure 2.

We refer to the code as a multilevel periodic code (ML-PC). The power coupling ratio s shown in Figure 2 determines the amount of power that is coupled to the loop shown in Figure 2 and that is coupled toward the Bragg grating. In extreme but unrealistic cases, when s is one, no power is coupled to the loop and the code will be only one pulse, when s is zero, all power will be coupled to the loop and no code will be generated. Realistic cases correspond to s so that $0 < s < 1$, i.e. a part of the power is coupled to the loop and a part is coupled toward the Bragg grating which is then reflected back to the ring. The part that is coupled to the loop will continue to observe other splits while traversing the coupler. Theoretically, this splitting will continue infinitely, generating an infinite length sequence. The power level of the pulses will decrease in the sequence due to the coupling where the first pulses have the higher power level and the code can be truncated to the first w pulses.

Let ρ_j be the j^{th} pulse power level generated by the encoder and sent back to the CO. The first pulse ρ_1 corresponds to the part of the power that goes through the coupler forth and back generating a power $\rho_1 = s^2$.

For $j=2$ and above, the level of ρ_j can be iteratively derived as

$$\rho_j = \begin{cases} s^2 & , j = 1 \\ (1-s)^2 s^{j-1} + (1-s)\rho_{j-1}, & j = 2, \ldots, w \end{cases} \quad (1)$$

where w is the weight of the code.

The total power for any code with weight w is expressed as

$$P_t = \sum_{j=1}^{w} \rho_j \quad (2)$$

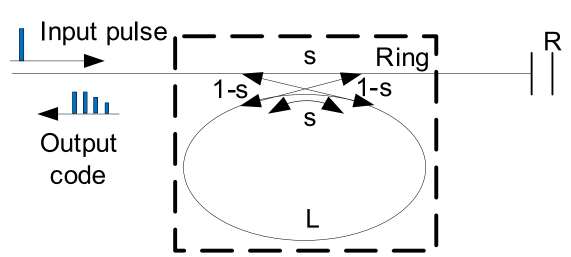

Figure 2. Novel encoder structure.

Figure 3 is a plot of the coupling ratio and the total power of the code for some values of w. We notice that for $w \leq 5$, the total power of the code increases as s increases. For $w > 5$, there are some values for s that cause decreasing in the total power of the code.

In the design of the codes, we seek to concentrate the reflected power in the first pulses. This avoids long codes with greater interference between codes. Also we seek to distribute this power so that all the pulses of the code have power as large as possible. Figure 4 is a plot for the first four pulses at different values of s between 0.1 and 0.9 which shows the distribution of the power among these pulses. We notice visually from Figure 3 and Figure 4 that the interval of s between 0.5 and 0.6 gives good distribution (or flatness) for the power between the pulses with cumulative power that depends on the code weight w.

The length of the code is determined by the silent period between the pulses which is physically equal to the length of the loop L, shown in Figure 2. This length is given as

$$F = pwT_s / c \quad (3)$$

where c is the speed of light. We need to make F as short as possible so that we reduce the effect of interference from the other customers. So choosing w is a tradeoff between the code length and the accumulative power of the code.

IV. Performance evaluation

A. Signal to noise ratio

To evaluate this monitoring system with the proposed encoder, we use the SNR as a measure of the performance.

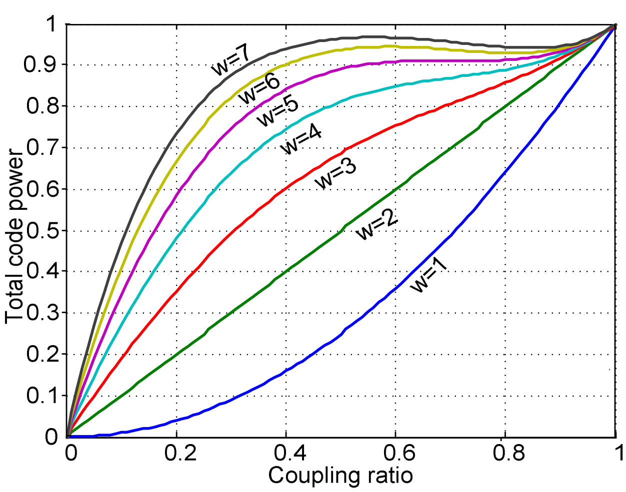

Figure 3. Total code power as a function of code weight and coupling ratio.

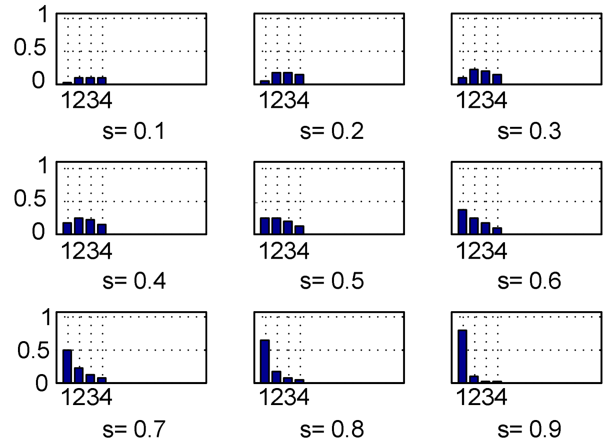

Figure 4. Code pulses level with weight 4 and coupling ratio between 0.1 and 0.9.

The SNR can be expressed as

$$SNR = \frac{\overline{\sigma_s}^2}{\overline{\sigma_n^2}} = \frac{\overline{\sigma_s}^2}{\sigma_{BN}^2 + \sigma_{RIN}^2 + \sigma_{DN}^2 + \sigma_{SN}^2 + \sigma_{TN}^2} \quad (4)$$

where σ_s is the desired signal and σ_n^2 is the noise power [12-16]. The noise power in (4) is the sum of the power of all noises that are added to the desired signal where BN is the beat noise, RIN is relative intensity noise, DN is the dark noise, SN is the shot noise and TN is the thermal noise.

The geographical distribution of the customers is also affecting the detection process at the CO and hence the performance of the monitoring system. It is found that the uniform radial (UR) distribution, an analytically tractable distribution; gives good performance estimation and can therefore be a useful tool in characterizing performance in terms of SNR [16-17].

B. Enhanced SNR via noise averaging

The decoded and detected signal in the CO consists of the sum of the power coming from the desired encoder with a noise term. In an effort to reduce the noise level, we repeat the measurement n times and then average the noisy signals. We then reduce the variance of the noise component assuming that the repeated measurements are independent and the measurement conditions from one measurement to another do not change. This technique has been previously exploited in optical OTDR systems called correlated OTDR [13]. By repeating the measurements n times, the average noise power is $\overline{\sigma_{n-ave}^2} = \overline{\sigma_n^2} / n$ and the SNR can be improved by *10log n* dB [18].

In monitoring systems, the monitoring signal can be transmitted periodically during a short time interval without affecting the operation of the system which is not

the case when the transmitted signal is data that needs to be transmitted continuously. This allows us to retransmit the signal n times and then average the detected signal to reduce the noise variance.

In our monitoring system, we assumed that the distance from the CO to the customer is approximately 20 km. The round trip time (RTT), including the processing time is then approximately 2 ms. For instance, a delay of 20 ms which is acceptable in our monitoring system allows us to repeat the measurements 10 times and hence achieve ~10 dB improvement in SNR.

C. Numerical results

Consider a PON network with $T_s = 1ns, P_s = 4dBm$ and by using the parameters and values in the table I, we can plot the SNR as a function of the number of customers for this monitoring system where we assumed a uniform distribution of customers in an area where the furthest customer's distance from the RN is small as compared to the feeder length. . In Figure 5, for 32 PON customers, our proposed monitoring system achieves 12.4 dB SNR in only one short measurement. This SNR can be improved as we mentioned in section V by averaging the noisy signals. With n= 10, we can get SNR~10 dB for 128 customers within 20 ms measurement time. Similarly, Figure 5 shows also that in order to monitor a PON having 256 network legs, we need n= 50 repetitions, hence 100 ms measurement time approximately.

V. Conclusion

We proposed and analyzed a new optical coding device that offers a promising solution for monitoring of future high-capacity PONs. We derived a mathematical model for our monitoring system and we used this model to address the importance of the network size on our monitoring system. Our optical encoding technique can support monitoring a network of 32 clients distributed uniformly with SNR > 10 dB in one shot. This SNR can be improved to support higher capacity PONs of 64, 128 and 256 by averaging the noisy signals.

Table I. Parameters used in the simulation

parameter	value
Code weight and coupling ratio	w=4, s=0.5
Fiber attunation coefficient	α_a = 0.3 dB/km
Total connector splice loss	α_L = 5 dB
Avalance photodiode	G = 100
Optical source bandwidth	B_o = 1 THz
Dark noise	I_{DN} = 160 nA
Thermal noise	$N_{TN} = 10^{-26}$ Amp^2/Hz
Feeder length	l_f = 20 km
Fiber fault probability	P_0 = .01

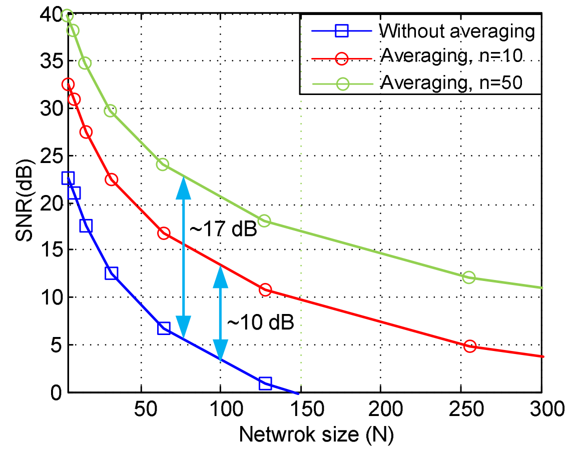

Figure 5. SNR versus network size.

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