Novel Coding for PON Fault Identification

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***Abstract*—In this paper we propose a novel simple periodic optical encoder for centralized fault monitoring of fiber-to-the-X (FTTX) passive optical networks (PONs). This optical encoder exploits a fiber ring with a different length for each distribution/drop fiber to produce a different periodic code. This reduces the cost of monitoring system while maintains good performance and high capacity. We investigate the design issues of this coding based monitoring system and evaluate its performance in terms of signal to noise ratio (SNR), probability of false alarm (PFA) and probability of misdetection (PMD). We obtain an SNR of 12.5dB for a 32 customers network in one shot measurement. By repeating the measurement multiple times we achieve a capacity of 64 to 256 in expense of longer measurement time. Moreover, the system accomplishes a PMD $\approx 2 * 10^{-9}$ for a PFA= 10^{-6} in a 64 customers network in 4ms.**

***Index Terms*—Network monitoring, optical coding/decoding, passive optical network (PON), FTTX, FTTH.**

I. Introduction

FIBER to the X (FTTX) promises a major role in alleviating the last mile bottleneck in the next generation broadband access networks. However, despite its advantages, established FTTX passive optical network (PON) with point to multipoint (P2MP) architecture still misses complete fault monitoring capability, i.e. it needs additional devices and equipments for physical layer testing, measurement and monitoring functions [1]. Ideal fiber fault monitoring in PONs involves two levels. The first is fault detection function that identifies the faulty branch in the tree network. The second is localizing the exact location of the fault inside the identified faulty branch. PON monitoring can save considerable operational cost. It is found that more than the third of service disruptions are due to fiber cable problems, e.g. fiber cut, break, fissure, aging, bending, etc. according to the Federal Communication Commission (FCC) [2].

Most monitoring systems used for fault detection employ optical time domain reflectometer (OTDR) [3]. 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 [4]. Several methods have been proposed to overcome this problem [5], [6]. Most of these solutions are impractical, mainly because of their limited capacity in terms of number of customers, their high cost or their deployment constraints such as fixing the length of the branches or manufacturing them with different core diameters. In the next generation PON (NG-PON) requirements, it is desirable that such monitoring be available regardless of the optical network terminal (ONT) is in service or even not connected [7]. This cannot be achieved using decentralized monitoring approaches where active devices are embedded inside the ONTs that measure the performance and then report to the central office (CO).

Manuscript received September 26, 2010. The associate editor coordinating the review of this letter and approving it for publication was N. Ghani.

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This research was done with the support of the Research Center of the College of Engineering, and The National Plan for Science and Technology, Saudi Arabia, Grant No: 09-ELE667-02. The authors acknowledge Prince Sultan Advanced Technologies Research Institute (PSATRI), Saudi Telecommunication Company (STC), and King Abdul Aziz City for Science and Technology.

Digital Object Identifier 10.1109/LCOMM.2011.041811.101805

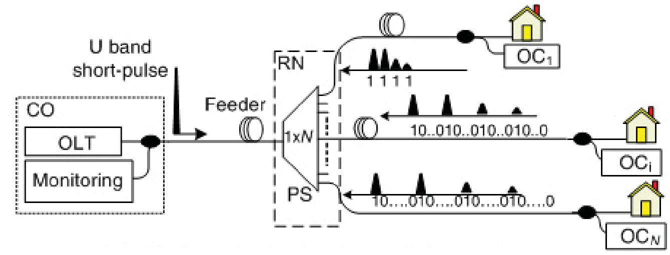

Fig. 1. Principle of optical coding monitoring system.

In [8], the authors initiated the concept of using optical coding, which is a modified scheme of standard optical code division multiplexing (OCDM), to enable an optical centralized monitoring system for fault detection in P2MP networks. 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. Multilevel periodic coding was introduced and experimentally demonstrated in [9] using two fiber Bragg gratings (FBGs).

In this paper, we propose a new periodic coding scheme which is well adapted to the FTTX-PON centralized monitoring system. This coding approach further reduces the overall cost of the monitoring system compared to [9] by involving lower cost optical coding devices (one ring of fiber and one simple 100% reflective FBG). In our analysis we also estimate the receiver operating characteristics (ROCs) of the proposed system in terms of probabilities of false alarm (PFA) and misdetection (PMD). Note that any increase of the PMD and/or PFA directly increases the operational cost.

One technique to reduce the effect of the noise and hence increase the system capacity in expense of larger measurement time is noise averaging thanks to repeating and averaging the measurement *n* times. In this paper, we use averaging in order to enable the monitoring of 64, 128 and 256 customers network while maintain PMD and PFA both lower than 10^{-5}.

In Section II, we describe the monitoring system and design issues of the proposed coding module. In Section III, we evaluate the performance of the proposed system through the signal to noise ratio (SNR), enhanced SNR and ROCs.

II. Monitoring System and Encoder Design

Figure 1 illustrates the principle of the optical coding based monitoring system, where a short pulse in the U band (1625-1675nm), with peak power P_s and duration T_s is transmitted from the CO down to the network. This pulse splits into N subpulses at the remote node (RN) passive splitter, dispatched through the distribution and drop fibers (DFFs) to all ONTs.

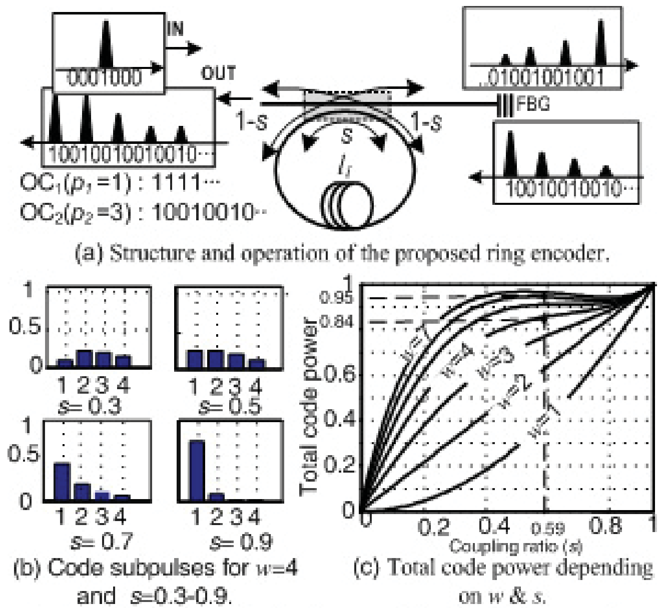

Fig. 2. Structure and design issues of the proposed encoder.

Each DDF drop is terminated by an encoder that generates back a unique code and is located physically close to the ONT. Each subpulse close to the ONT $_i(i = 1, .., N)$ is encoded and reflected back to the CO by the respective optical encoder OC $_i$. Information on individual DDFs at the CO is discernable thanks to the orthogonality between codes.

A single incident pulse generates a code composed of w multilevel subpulses that are equally spaced with a spacing p_i where i denotes the i^{th} customer. Each customer has a Bragg grating with 100% reflectivity and a ring of fiber with length l_i as shown in Fig. 2(a). The power coupling ratio s determines the amount of power coupled to the loop and that is passed 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 $0 < s < 1$. 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 decaying sequence. The first subpulses in the sequence have the higher power level and the code can be truncated to the first w subpulses that become the weight of the code. This encoder theoretically operates as 100% mirror, since all the incident power is reflected.

Let ρ_j be the j^{th} subpulse power level generated by the encoder and sent back to the CO. The first subpulse ρ_1 is obviously equal to $\rho_1 = s^2$. For $j = 2$ and above, the level of ρ_j can be iteratively derived as

$$\rho_j = (1-s)^2 s^{j-1} + (1-s)\rho_{j-1}, j = 2, ..., w \qquad (1)$$

The total power for any code with weight w is $P_t = \sum_{j=1}^{w} \rho_j$. Fig. 2(b) illustrates the first four subpulses for different values of s between 0.3 and 0.9 and shows the distribution of the power among these subpulses. Fig. 2(c) plots the total reflected power in the code as a function of the coupling ratio and the weight of the code w. We notice that for $w \leq 5$, the total power of the code increases as s increases. For $w > 5$, there is a value range of s that decreases the total power of the code. In the design of the codes, we seek to concentrate the reflected power in the first subpulses. This avoids long codes with greater interference between codes. We notice visually from Fig. 2(b) and Fig. 2(c) that the interval of s between 0.5 and 0.6 gives good distribution (or flatness) for the power between the subpulses with cumulative power that depends on the weight w. The codes length of the i^{th} customer is determined by the silent period between the subpulses and is given as

$$l_{ci} = p_i w T_s c \qquad (2)$$

where c is the speed of light and $p_i = l_i / cT_s$ is an integer number that determines the length of the i^{th} encoders ring l_i. The minimum ring length corresponds to the physical length of the pulse because this avoids overlap between successive chip pulses in the code with a period $p_1 = 1$. In our simulation, we use $T_s = 1$ns that corresponds to ≈20cm physical ring length. Compared to the FBGs encoder in [9] where two gratings are required with two different reflectivities; this encoder replaces the low reflectivity grating by a 2x2 coupler, hence further decreasing the encoder cost. We note however, that FBGs encoder is 12% more power efficient for w=4. We hence chosen w=6 in our design in contrast to w=4 in FBGs encoder design reducing the coding loss down to 5%.

III. Performance Evaluation

A. Signal to Noise Ratio (SNR)

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

$$SNR = \frac{\overline{\sigma_s}^2}{\overline{\sigma_n^2}} = \frac{\overline{\sigma_s}^2}{\overline{\sigma_{BN}^2} + \overline{\sigma_{RIN}^2} + \overline{\sigma_{DN}^2} + \overline{\sigma_{SN}^2} + \overline{\sigma_{TN}^2}} \qquad (3)$$

where $\overline{\sigma_s}^2$ and $\overline{\sigma_n^2}$ are the average desired signal and noise power respectively. The later 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 current noise, SN is the shot noise and TN is the thermal noise.

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 approximately$10log(n)$dB. The measurement time depends on the round trip time (RTT) between the CO and the furthest ONT (i.e. 20km apart) in addition to the delay caused by the encoder. In our simulation, we considered a number of customers from 4 up to 256 to show the scalability of this technique for future higher network size. For this capacity and using a simple algorithm to generate orthogonal code with w=6, the length of the ring is $l_{256} = 100$m with p_{256}=500. Using (2), the maximum time delay of the encoder is 3μs which is small compared to the RTT and can be neglected.

In our simulation, we consider a PON with T_s=1ns, P_s=4dBm and using the parameters and values in Table I, we plot the SNR as a function of the number of customers. In Fig 3(a), our proposed monitoring system achieves 12.4dB SNR for a 32 PON customers in only one shot measurement. This SNR can be improved by averaging: with n=10, we obtain SNR ≈10dB for 128 customers within 2ms measurement time. Similarly, Fig. 3(a) shows that for a 256 customers network, we need n=50 for 10ms measurement time.

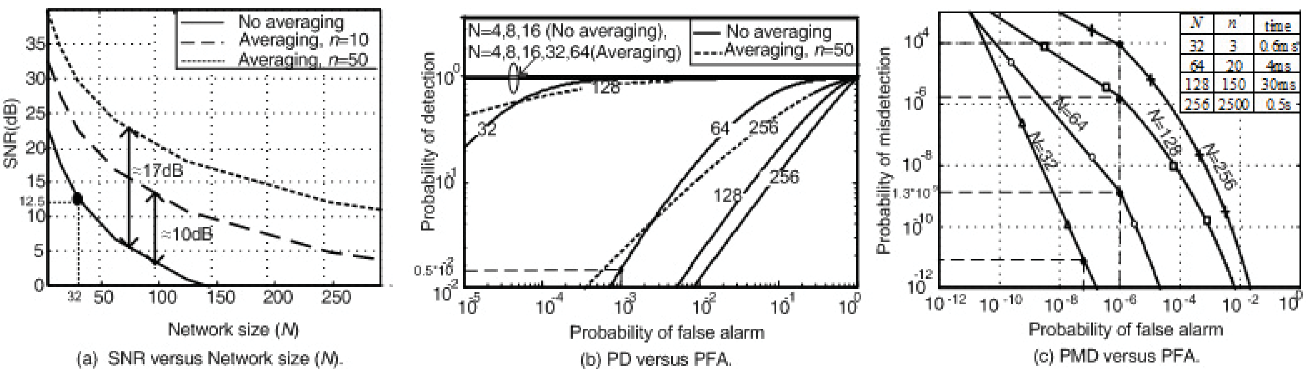

Fig. 3. Obtained performance in terms of SNR, PMD and PFA.

TABLE I
PARAMETERS USED IN THE SIMULATION

Parameter	Value
Code weight and coupling ratio	w=4, s=0.5
Fiber attunation coefficient	α_a=0.3dB/km
Total connector/splice loss	α_L=5dB
Source bandwidth and APD gain	B_0=1THz, G=100
Feeder length	l_f=20km
Dark noise	I_{DN}=160nA
Thermal noise	$N_{TN} = 10^{-26}$A ^{2}/Hz

B. Receiver Operating Characteristics (ROCs)

At the receiver, the desired branch code is corrupted by the detection noise and cross correlation interference coming from non perfect orthogonality between codes. The receiver needs to make a decision whether a received noisy signal represent faulty or healthy branch. Any wrong decision may cause the CO to misdetect a faulty DDF or falsely declare a broken fiber as a healthy DDF. Both wrong decisions induce operational cost, the former leads to customer dissatisfaction and complaints and the later results in unnecessary truck-roll and technician dispatching in the field.

For our monitoring application, there exists no prior knowledge about the average probability of fault in the literature so Neyman-Pearson test criterion is appropriate [10]. This criterion is based on maximizing the probability of detection (P_D) while not allowing the probability of false alarm (P_{FA}) to exceed a certain value. A plot of the relationship between P_D and P_{FA} is known as receiver operating characteristics (ROCs) [10]. We define P_D as the probability of correctly declaring a DDF faulty and P_{FA} as the probability of declaring a DDF faulty when it is healthy. The ROC for our monitoring system is shown in Fig. 3(b). For small network size, i.e. N $\leq$16 with no averaging, the ROC is flat and P_D $\approx$1 for any value of P_{FA}. As the network size increases, the SNR decreases and the ROC deteriorates. For instance, for N=64 and $P_{FA} = 10^{-3}$, the detection probability reduces to a poor value of $5 * 10^{-3}$, i.e., only 5 faults out of 1000 will be detected. To improve the system performance, we use noise averaging pushing up the P_D to $\approx$0.999 for 64 customers with $P_{FA} < 10^{-5}$. In our system, while no real statistics are available in the literature, it is reasonable that P_D should be very close to 100% while P_{FA} should be minimized. We found it is more appropriate to define our ROCs as probability of misdetection (P_{MD}) versus P_{FA}. This probability is defined as the probability of declaring no fault whereas there is a fault and is given as $P_{MD} = 1 - P_D$.

A plot for P_{MD} versus P_{FA} is shown in Fig. 3(c). It is noticed that the P_{MD} for N $\leq$16 is very small so that it does not appear in the figure. For larger *N*, noise averaging is used to improve the performance of the system. As shown in Fig. 3(c), for *N*=64 with $P_{FA} = 10^{-6}$, $P_{MD} = 1.3 * 10^{-9}$ which means approximately 2 faults out of 10^9 will be misdetected in 4ms measurement time. To maintain the same P_{FA} for *N*=256, averaging time of 0.5s is needed to get $P_{MD} = 10^{-4}$.

IV. Conclusion

We proposed and analyzed a new optical coding device that offers a promising solution for monitoring of future high capacity PONs. Our technique can support monitoring a network of 32 clients with an SNR>12dB in one shot, and higher number of customers using measurement averaging. We found that for *N*=32 (respectively 128), we need 0.6ms (respectively 30ms) measurement time to achieve P_{FA} and $P_{MD} < 10^{-7}$(respectively$< 10^{-5}$).

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