A Novel Pulse-Positioned Coding Scheme for Fiber Fault Monitoring of a PON

Mohammad M. Rad, Habib A. Fathallah, Martin Maier, Leslie A. Rusch, and Murat Uysal

***Abstract*—In this letter, we propose a novel optical coding scheme for fiber link quality monitoring of a passive optical network (PON). The proposed scheme named incrementally pulse positioned coding (IPPC) is practically very attractive due to its simple design and fabrication process, small size, zero coding loss and low cost. We demonstrate the superior correlation properties of IPPC over existing codes, address the design considerations, and evaluate its performance for a PON monitoring system via the average signal-to-interference ratio (SIR).**

***Index Terms*—Monitoring, incrementally pulse-positioned coding (IPPC), passive optical network (PON).**

I. Introduction

OPTICAL coding (OC) has been proposed for fiber link quality monitoring of passive optical networks (PONs) [1], [2]. In this approach, a unique code is assigned to the fiber branch for each customer, i.e., distribution-drop fiber (DDF). Passive optical encoders (located at the very end of each DDF) encode the transmitted U (1625-1675nm) band monitoring signals. The central office (CO) receives the sum of all the encoded monitoring signals and assesses the quality of the individual link by exploiting the features of the autocorrelation peak.

In principle, most coding schemes commonly used in optical code-division multiple-access (OCDMA) systems can be applied to OC monitoring [4]. Although they provide acceptable performance, multi-wavelength optical orthogonal codes (MW-OOCs) are not of practical interest due to their technical and practical challenges for the monitoring system. A large number of components, high insertion loss, large size, and low scalability are the main disadvantages of standard coding techniques for monitoring applications [5]. It should be noted that such challenges in code design for monitoring are quite distinct from those of data communications; extremely low cost encoders need to be designed to optimize location detection (rather than bit detection in data communication).

Recently periodic codes (PCs) have been proposed and successfully investigated for an experimental demonstration of PON monitoring using OC technology [3], [5]. PCs (compared to MW-OOCs) are simple to design and easy to handle. However, they suffer from some serious technical and practical challenges. Among others, due to their poor correlation characteristics, the network recognition process is still challenging and requires exhaustive search algorithms [3]. The partial reflectivity of the first grating imposes encoding loss and makes the total impulse response of PCs sensitive to the fabrication process. The required fiber length to implement the encoders is still very long for very large network sizes (i.e., larger than 64 users).

In this letter, we propose a new coding scheme that we call incrementally pulse-positioned coding (IPPC) for PON monitoring applications. It provides better correlation characteristics, zero encoding loss, and better performance in comparison to PCs. More importantly, our proposed scheme helps to reduce significantly the overall cost of OC monitoring systems and thus meets the cost constraints of PONs.

II. Challenges of PCs for PON Monitoring

PCs are implemented using two fiber Bragg gratings written for the same waveband; the first is partially reflective ($R_1 = 38\%$), and the second acts as a frequency selective mirror ($R_2 = 100\%$). The patchcord length between gratings is optimized for the best correlation characteristics, see Fig. 1(a). Despite the successful experimental demonstration of OC PON monitoring using PCs [3], these codes suffer from serious challenges in practical monitoring deployments. These challenges can be summarized as follows.

- *Sensitivity of the impulse response*

Any deviation from 38% (reflectivity of the first grating) as a result of imperfect fabrication process, dramatically affects the amplitude of the encoded sequence. An accurate fabrication process is necessary to precisely write gratings with fixed reflectivity for the U band pulses.

- *Encoding insertion loss*

Due to partial reflection of the first grating the insertion loss is 4.2 dB for PC encoders. Considering that no U band amplifier exists, this loss reduces the total loss margin of the monitoring system [7].

- *Very long patchcords for large network size*

While being small in size compared to standard coding schemes, the required patchcord length for a PC significantly increases as the network size increases. This is more problematic especially for future large size PONs [8], [9].

- *Poor correlation characteristics*

The correlation characteristics of the codes affect the recognition process, i.e., localization of the encoders at the CO. High (out-of-phase) auto- and cross-correlation sidelobes increase the required processing time of the received monitoring data

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M. M. Rad is with the Department of Electrical and Computer Engineering, University of Waterloo, Canada (e-mail: mehdi.mansouri@gmail.com).

H. Fathallah is with the Department of Electrical Engineering, King Saud University, Saudi Arabia (e-mail: hfathallah@ksu.edu.sa).

M. Maier is with the Optical Zeitgeist Laboratory, INRS, Quebec, Canada (e-mail: maier@emt.inrs.ca).

L. A. Rusch is with the ECE Department, Université Laval, Quebec, Canada (e-mail: rusch@gel.ulaval.ca).

M. Uysal is with the Faculty of Engineering, Özyeğin University, 34662, Istanbul, Turkey (e-mail:murat.uysal@ozyegin.edu.tr)

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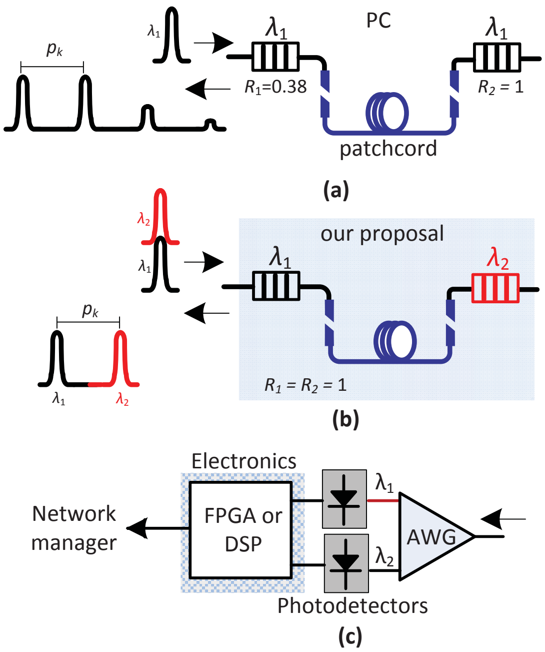

Fig. 1. a) Proposed periodic coding (PC); b) Proposed incrementally pulse-positioned code (IPPC), c) Digital implementation of IPPC decoder.

[3]. PCs have non-zero auto-correlation sidelobes. In addition, the infinite-length periodic sequence increases the partial interference effects and therefore reduces the efficiency of the monitoring system in localizing the encoders.

III. Proposed Scheme

A. Principle of Operation

In the proposed IPPC scheme, the two gratings in PC are tuned to reflect distinct wavelengths with 100 % reflectivity (Fig. 1(b)). As a result, a two-dimensional code is constructed [6]. For encoding, the CO transmits simultaneously two wavelength-orthogonal U band short pulses. Because the gratings are tuned to reflect distinct wavelengths, there is no internal reflection among the gratings, i.e., each encoded sequence contains two reflected pulses (Fig. 1(b)). As a result, the equivalent time-domain code length p_k $(k = 1, \ldots, K)$ reduces compared to an infinite sequence for PCs. The code weight is $w = 2$ for IPPCs versus $w = 4$ for PCs [6]. There is no encoder loss as the two transmitted pulses are totally reflected. The fabrication of the gratings with very high reflectivities (such 99%) is simple and of low cost. In addition, due to the decreased code length, the patchcord length is proportionally reduced, providing smaller size encoders for very large number of codes (users).

A digital implementation of the decoding operation requires an arrayed waveguide grating (AWG) and two U band detectors as illustrated in Fig. 1(c). The detectors are followed by an FPGA to digitally perform the decoding operation for each DDF [5]. Advanced signal processing techniques are applied to the detected signals for network recognition [3]. Note that the added complexity for IPPC is only present at the CO where cost can be amortized while savings are made on encoders to be located at customer premises.

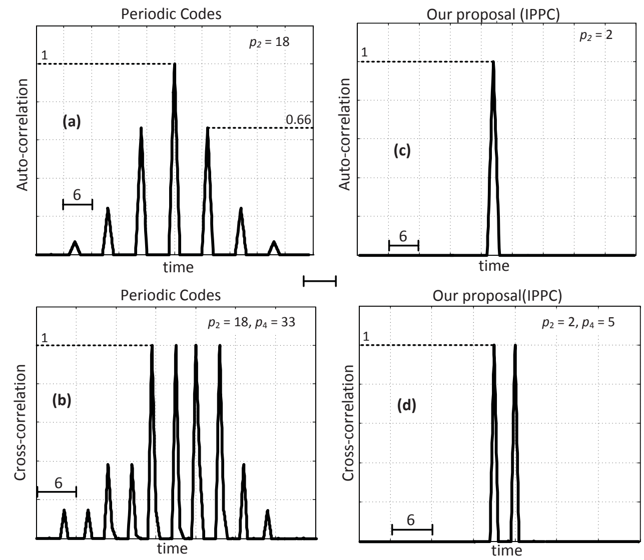

Fig. 2. Normalized auto- and cross-correlation functions for PC and IPPCs.

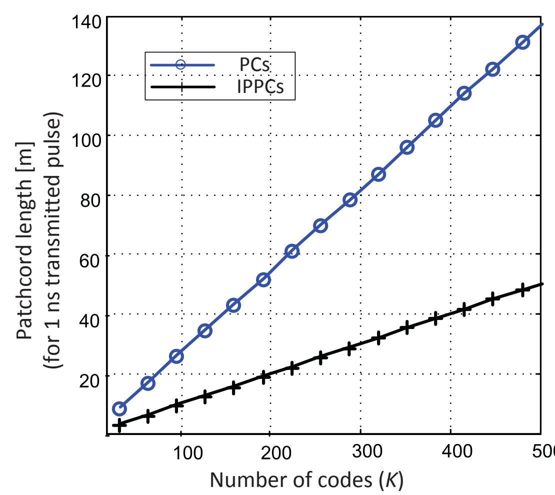

Fig. 3. The required patchcord length in meter versus the number of codes for PCs and IPPCs.

B. Statistical Properties of IPPCs

Figure 2 shows the normalized correlation functions of IPPCs and PCs; assuming various values of code lengths p_k. For PCs, codes are generated using the algorithm in [5] assuming $w = 4$. However for IPPCs (with $w = 2$) the set of $p_k = k$ provides the optimal solution (i.e., minimal cross-correlation). As we observe (from the upper part of Fig. 2a and c), no auto-correlation sidelobe exists for IPPCs due to the wavelength domain coding. Indeed, the normalized auto-correlation sidelobe peak decreases from 1.48 for PCs to zero for IPPCs. Additionally, the length of the auto-correlation pattern decreases from $2p_k$ for PCs (Fig. 2a) to 2 for IPPCs (Fig. 2c).

The cross-correlation of IPPC (PC) is illustrated in Fig. 2d (Fig. 2b); considered code lengths are specified in the figure. As no partial reflection exists for IPPCs, the length of the cross-correlation pattern as well as spikes reduces considerably. This proportionally reduces the interference effects in OC monitoring systems [11]. Hence, the quality of the monitoring signal is significantly improved for each encoder (user). More importantly, the better correlation characteristics, the network recognition process is less complex (i.e., lower degree of exhaustive search) for a system based on IPPC compared to PC.

In Fig. 3, we plot the required patchcord length versus the number of codes (number of users). A 1 ns pulse is considered for the transmitted pulse width [5]. As observed shorter patchcord lengths are required for the proposed IPPCs. This also renders encoders easier to handle and less bulky. It is worth mentioning that the number of codes generated in the existing families of MW-OOCs in the current literature is fixed once the values for the associated code properties are chosen. Such codes do not provide a scalable solution. However, similar to PCs, our proposed scheme overcomes this limitation for practical deployment. It should be further emphasized that the three elements (two fiber gratings with 100% reflectivities and one patch cord) required for fabrication of IPPCs are very well developed and available in the market for a cost-effective production. Therefore IPPC is very well adapted for practical application.

IV. Performance Evaluation via Signal-to-Interference Ratio

In this section, we evaluate the performance of an OC monitoring system employing IPPCs through the calculation of signal-to-interference ratio (SIR). We consider only the interference effects and neglect other noise sources such as shot, beat, and relative intensity noise as they can be effectively removed by employing standard averaging techniques in monitoring applications [3], [10], [11]. We define SIR as

$$SIR = \left[\frac{w}{\sum P_{in}^{(k)}}\right]^2 \tag{1}$$

where the numerator is the auto-correlation peak (equal to the code weight w), and the denominator is the average of the interference. $P_{in}^{(k)}$ is the average interference affecting the encoder with a code length of p_k. From [11], it can be calculated as

$$P_{in}^{(k)} = \frac{1}{K-1}\sum_{m\neq k} P_{in}(m,k) \times Pr(\ell_{m,k} < \ell_{CD}^{(m,k)}) \tag{2}$$

where K is the number of encoders, $P_{ik}(m,k)$ is the mutual interference probability between codes m and k, and $P_{in}(m,k) = \frac{w^2}{2M\times max(p_m,p_k)}$. The factor M denotes the number of wavelengths employed for coding; $M = 2$ for IPPCs and $M = 1$ for PCs. Here, $\ell_{m,k}$ is the physical separation between the two encoders and $\ell_{CD}^{(m,k)}$ is their effective correlation distance. By definition we have $\ell_{CD}^{(m,k)}$ =max$(\ell_{CD}^{(m)}, \ell_{CD}^{(k)})$ and $\ell_{CD}^{(k)} = cT_c p_k/2$, where $c = 2\times 10^8$ m/s is the light speed in the fiber core and $T_c = 1$ ns is the transmitted pulse width [11].

Figure 4 illustrates the SIR as a function of the number of users (encoders) for both IPPC and PC schemes. The users are considered to be uniformly distributed (i.e., uniform radial distribution) over a 1 km^2 coverage area [11]. Significant improvement is achieved for the measured SIR by employing

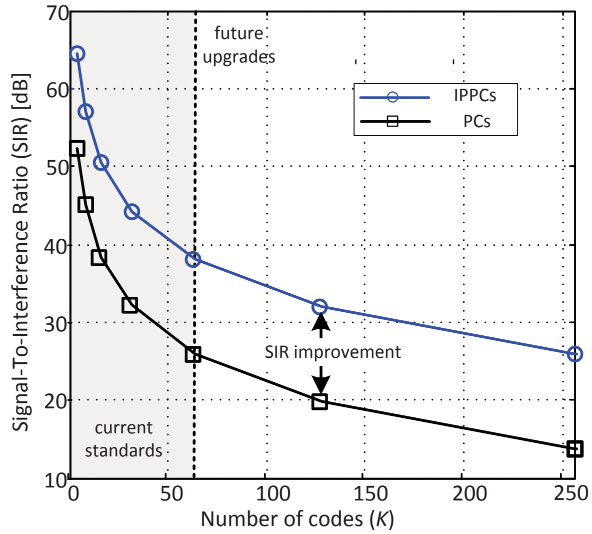

Fig. 4. SIR versus the number of codes for both IPPC and PC schemes.

IPPCs compared to PCs. For instance, for K=256 users, IPPC provides SIR=26dB compared to SIR=13dB for PCs. Such large gains are possible due to the fact that our proposed scheme has better correlation properties, therefore suffers less from interference compared to a system based on PC scheme.

V. Conclusion

We proposed a new coding scheme which is scalable and has low complexity for PON monitoring. The proposed scheme has better correlation characteristics, imposes no coding loss, and is less bulky. Our analysis shows that the proposed solutions provides superior performance in terms of SIR compared to previously reported coding schemes adapted for PON monitoring.

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