Beat Noise Mitigation via Hybrid 1D/2D-OCDM: Application to Monitoring of High Capacity PONs

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Abstract: We propose novel PON monitoring using a hybrid optical code division multiplexing (OCDM) scheme that mixes one and two-dimensional coding principles. We simulate monitoring of PON with 256 customers at low cost per branch.

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1 Introduction

As the capacity of passive optical networks (PONs) increases, both the importance of network monitoring and its complexity increase [1-4]. In [5], the monitoring of a limited capacity PON (4 customers) was demonstrated by exploiting Brillouin scattering. This requires that distribution/drop fibers (DDFs) be manufactured with different physical characteristics that generate and return different Brillouin frequencies. In addition to involving high capital and operation expenditure (CAPEX and OPEX), this technique would have a dramatic impact on existing fiber network infrastructures.

In [4] we applied, for the first time to our knowledge, a modified scheme of optical code division multiplexing (OCDM) for centralized monitoring that promises a capacity of hundreds of customers. We suggested the use of a single U band (ITU standard for monitoring) laser together with passive splitters/combiners or multiple fiber Bragg grating (MFBG) based 1D coding scheme. In [6], we simulated the system signal to noise ratio (SNR) and found that a broadband source (BBS) greatly outperforms a laser source. The latter suffers severely from excessive beat noise, arising between pulses that contribute to the auto-correlation peak and those interfering pulses falling in the detection window. This dramatically degrades system performance even for very low capacity networks.

The main purpose of this paper is the development of a new monitoring architecture that exploits hybrid one- and two-dimensional (1D/2D) coding principle to reduce the system beat noise. To the best of our knowledge, this is the first time that hybrid 1D/2D is proposed as a solution that remedies the beat noise problem in any OCDMA system. In this paper, we focus on coding-based monitoring only. We find that our proposal allows the monitoring of more than 256 customers, while maintaining low cost/per DFF (or customer) and acceptable SNR>15dB.

2 Hybrid 1D/2D Coding Scheme

2.1 Beat and RIN Noises in OCDMA

All OCDMA systems and more particularly the 1D time-coding scheme, suffers greatly from relative-intensity noise (RIN) and beat noise (BN). The RIN quantifies the amount of intensity fluctuation and exists for all sources. Incoherent sources (i.e., BBS) show very high RIN, while coherent light sources (i.e., lasers) generate negligible RIN because of their high damping ratio. Consequently, systems based on lasers suffer from BN only, and those based on BBS suffer from both RIN and BN. BN arises from reception of a sum of in-time superposed optical pulses, whose spectral separation is closer than the receiver's electrical bandwidth [8]. Hence, the detection of an auto-correlation peak composed of multiple pulses carried by the same (or nearly the same) wavelength observes important beat noise superposed with the detected signal.

In [6] we found that a 1D coding scheme, while simple and cost effective, suffers severely from RIN and BN (arising by the beating of pulses composing the auto-correlation peak). In order to alleviate the BN, 2D (wavelength-time codes) can be applied as in standard OCDMA [7]. While exhibiting good performance, this technique is expensive due to the high number of fiber-Bragg gratings (FBGs) required at the encoders, here referred as coding mirrors (CMs).

In order to address this problem we propose a novel and cost effective hybrid 1D/2D coding scheme. This combines both advantages: the low cost of 1D coding at the customer end and the beat noise cleaning capability of 2D coding. In addition, our solution does not modify existing network infrastructure, and concentrates complexity at the CO, amortizing the cost over all customers.

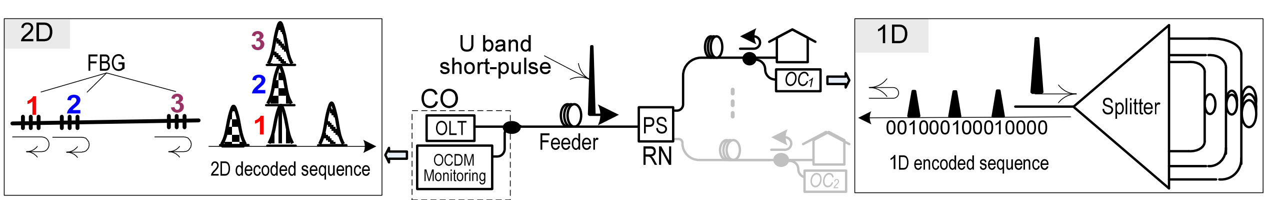

Fig. 1. Hybrid 1D/2D-OCDM for fiber fault monitoring in PON.

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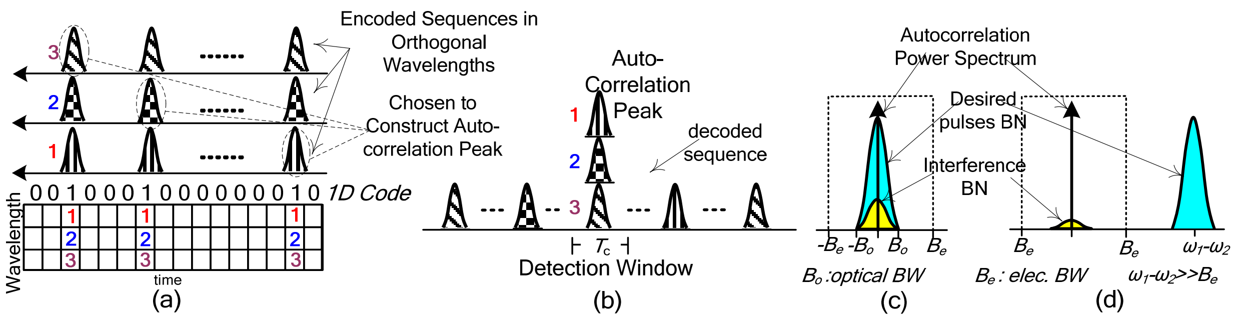

Fig. 2. Hybrid 1D/2D: (a) 1D code inscribed into each wavelength, (b) 2D decoder output: autocorrelation of pulses carried by different wavelengths; (c) BN power spectrum of 1D, and (d) BN power spectrum of hybrid 1D/2D.

2.2 Principle of hybrid 1D/2D OCDM monitoring system

Our new monitoring concept is based on the use of three key elements. First, our optical source is required to be multi-wavelength, consisting of a comb of U band lasers. Second, our CMs placed at the DDF ends remain passive splitters/combiners as in the case of 1D coding scheme [4,6]; codes are unchanged. Third, at the CO we perform intelligently a two dimensional decoding over the reflected spectrum using 2D decoders made of MFBGs, see Fig.1.

The operational principle of our hybrid OCDM is illustrated in Fig. 2. In this scheme, the monitoring equipment located at the CO sends a comb of pulsed wavelengths to the network, as in the case of standard 2D. The 1D encoders' outputs at the DDF end will be reflections of w (code weight, 3 in the illustration) replicas of wavelength-orthogonal 1D encoded sequences. In Fig. 2a we see a 1D code that has generated with three wavelengths for each pulse.

At the CO, the decoder is a standard MFBG 2D decoder (see Fig.1) that superposes w pulses by selecting a different wavelength in each of the w time slots. Indeed, from all the sequences coming from the desired one (Fig. 2a), only circled chips (constructing autocorrelation peak) are chosen, each from a different wavelength as shown in Fig. 2b. Every Bragg grating reflects about 95% of the input pulse at its centre wavelength. The 2D decoder introduces delays between the pulses of different wavelengths compensating for the relative delays introduced in its respective 1D encoder. Using FBG decoder scheme has two main advantages with respect to passive splitter/combiner decoder: 1) it decreases the total loss experienced by an optical pulse by w^2 (for code weight w); and 2) the 2D aspect of our hybrid scheme eliminates the beating between the pulses coming from the desired CM and contributing to the construction of the autocorrelation peak.

2.3 Beat Noise Cleaning of Hybrid 1D/2D Scheme

In Fig. 2c, we observe the spectral distribution of the beat noise in a standard 1D scheme. This is composed of two power peaks: one (the higher) comes from beating between the desired pulses constructing the auto-correlation peak, the other (lower) comes from the beating between desired pulses and interference pulses (signal-to-interference) and beating between interference pulses themselves (interference-to-interference). We see in Fig. 2d that our hybrid 1D/2D scheme moves the higher beat noise peak out of the electric band [$-B_e$,B_e], i.e., away from the desired auto-correlation peak spectrum (delta function in Fig. 2c and 2d). Similar to standard 2D coding, not only beating among desired pulses is eliminated, beat noise due to interference is also reduced by a factor equal to the code weight [8].

2.4 Coherent v.s. Incoherent Sources

On one hand, it is worth noting that our hybrid system eliminates the BN arising between desired pulses for both source types: coherent and incoherent. However, the BBS in the hybrid scheme is less attractive due to the RIN inherent to the BBS that becomes the dominant noise source. This disqualifies the BBS for our hybrid technique. In the next, we compare 1D-BBS based system with our laser based hybrid 1D/2D.

3 Performance analysis

3.1 Signal-to-Noise Ratio

We define the signal-to-noise ratio (SNR) as presented in the following equation,

$$SNR \triangleq \frac{\mu_{SIG}^2}{\sigma_N^2} \triangleq \frac{\mu_{SIG}^2}{\sigma_{TH}^2 + \sigma_D^2 + \sigma_{SH}^2 + \sigma_{BN}^2} \qquad (1)$$

where the index TH is used for thermal noise (spectral density 0.1 pA.Hz$^{-0.5}$ assumed), D for dark current (average current=160nA), SH for shot noise and BN for beat noise and μ_{sig} is the amplitude of the auto-correlation peak. We consider a laser source with 100 MHz linewidth and a broadband source (BBS) with 1 THz bandwidth, pulse duration of 1ns, pulse power of 4dBm, an avalanche photodiode (gain=100, excess factor=0.05), and an aggregate excess loss of 5 dB for splicing, connectors etc. We considered a 10 km feeder fiber between the CO and the remote node (RN) in Fig.1, and a uniform distribution for the distance between the ONUs and the RN over a fixed coverage area [6]. The desired DDF status (healthy or faulty) is modeled by a Bernoulli random variable with ½ healthy probability. We consider time-spreading codes defined by F, $w=4$, $\lambda_a=\lambda_c=1$; respectively the code length, weight, maximum out-of-phase auto, and cross-correlation values as in [6].

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Fig. 3a and 3b illustrate the SNR of our proposed hybrid 1D/2D coding scheme in comparison to 1D-BBS for two 0.25 km^2 and 2 km^2 coverage areas. While in 1D-BBS, beat noise power is always dominated by beating between desired pulses, in hybrid 1D/2D it is dominated by interference. Therefore, as the covering area increases the probability of interference decreases improving the SNR, around 6 dB for small capacities (<128) in Fig. 3a and 3b. For small network size, 1D-BBS performs better due to its huge bandwidth. But as the capacity increases, which increases the loss at the RN, other noises become dominant and SNR degrades significantly for both 1D and hybrid cases. Our proposed monitoring method allows up to 256 customers network to be monitored with an SNR of 16 dB. However, in principle, a concatenation of different hybrid systems side-by-side in the 50 nm U band easily increases the network capacity into the thousands while maintaining low cost for the encoders as in [6].

The SNR of our system can be further improved using a correlation technique largely used in OTDRs. This consists of repeating the measurement a number of times and averaging the obtained results. This technique improves the SNR proportionally to the number of measurements (or repetitions). For example in Fig. 3a and 3b the dotted curves show our system SNR by repeating the correlations only 10 times resulting to a 10dB improvement [9,10]. Hybrid 1D/2D with correlation technique provides a capacity of 512 customers with 20dB SNR (Fig 3a and 3b).

3.2 False-Alarm Probability

To study the receiver false-alarm probability we applied the Neyman-Pearson test to the receiver at the CO [11]. We investigate the receiver operating characteristic (ROC), i.e., false alarm probability P_{FA} vs. detection probability P_D. We considered the total noise to be Gaussian and assumed the same system parameters of section 3.1. The ROC of our hybrid 1D/2D scheme in a 0.25 km^2 coverage area is presented in Fig. 3c for different network capacities. It can be seen that for high network capacities (such as 256), ROC is wide enough. For instance in a 256 customers, while preserving small false alarms such as $P_{FA}=10^{-4}$, detection probability is very high, i.e., $P_D=0.99$.

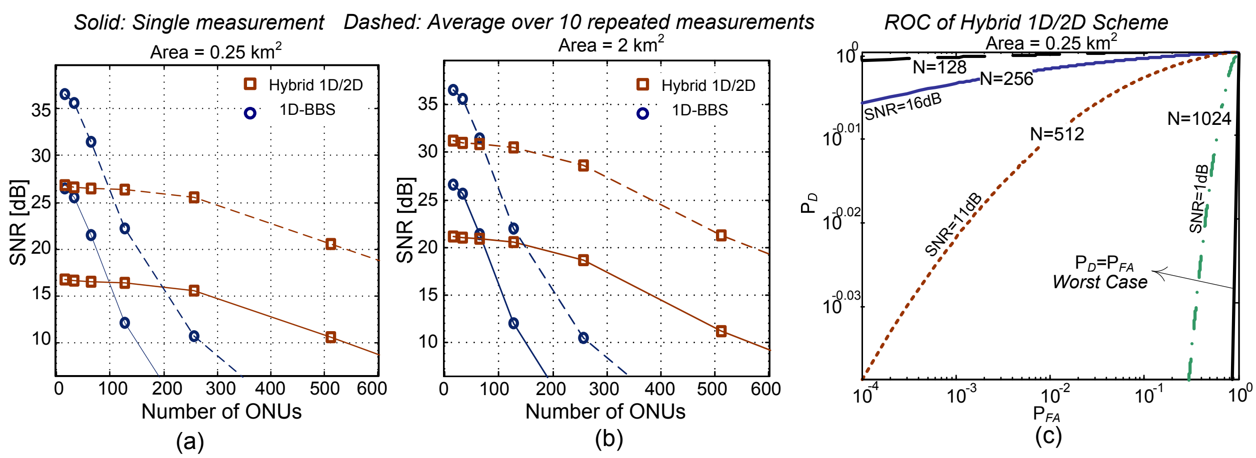

Fig.3 SNR versus network size for 1D-BBS and hybrid 1D/2D and for coverage areas 0.25km² and 2km², respectively, (c) ROC of Hybrid 1D/2D scheme for 0.25km² coverage area and no averaging.

4 Conclusion

We proposed a new hybrid 1D/2D coding scheme for fiber fault monitoring in PONs. We demonstrated that mixing 1D and 2D elements and characteristics is effective in mitigating the beat noise widely observed in 1D system. Our hybrid 1D/2D scheme reduces the encoding cost while maintaining acceptable performance, up to 256 customers with SNR higher than 16dB.

5 References

[1] A. Girard, *FTTx PON Technology and Testing*, EXFO Electro-Optical Engineering Inc., Canada 2005, ISBN 1-55342-006-3.
[2] Pfeiffer, *et al*., "Monitoring and protecting the optical layer in FTTH networks", in *Proceedings of the 2005 FTTH Conf*., 2005.
[3] Hann, *et al*., "Monitoring technique for hybrid PS⁄WDM-PON…," *Measurement Science and Technology*, 17(2006) pp. 1070-74.
[4] H. Fathallah, *et al*, "Code-division multiplexing for in-service out-of-band monitoring...," *J. Optical Networking*, vol. 6, no. 7, July 2007.
[5] D. Iida, *et al*, "Design of identification fibers with individually with …," *J. Lightwave Tech*., vol. 25, no. 5, May 2007.
[6] M. Rad, *et al*, "Effect of PON geographical distribution on monitoring by optical coding", *ECOC Sep. 2007*, Germany.
[7] H. Fathallah, *et al*., "Passive Optical Fast Frequency-Hop CDMA Communication System," *J. Lightwave Tech*., 17 (1999), pp. 397-405.
[8] L. Tansevski, *et al*., "Impact of the beat noise on the performance optical CDMA systems," *IEEE Comm. Letters*, vol. 4, no. 8, 2000.
[9] D. Derickson, *Fiber optic test and measurement*, Prentice Hall, 1998.
[10] M. Nazarathy, *et al*., "Real-Time Long Range Complementary Correlation ....", *J. Lightwave Tech*., vol. 7, no. 1, pp. 23 - 38, 1989.
[11] H. V. Poor, *An Introduction to Signal Detection and Estimation*, Springer, 1998, ISBN-10: 0387941738 .