Fiber Fault Monitoring for Passive Optical Networks Using Hybrid 1-D/2-D Coding

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***Abstract*—We propose a novel, simple, and cost-effective technique to decrease beat noise in standard one-dimensional (1-D) optical coding passive optical networking (PON) monitoring. This scheme places low-cost 1-D encoders at the termination of the network branches and two-dimensional (2-D) decoders at the central office mixing the 1-D and 2-D schemes in a complementary way. Simulation shows that our proposed scheme allows the monitoring of a 64 customer PON with a signal-to-noise ratio of 9.1 dB.**

***Index Terms*—Beat noise (BN), false alarm probability, hybrid one-dimensional/two-dimensional (1-D/2-D) optical code-division multiplexing (OCDM), passive optical networking (PON) monitoring, signal-to-noise ratio (SNR).**

I. Introduction

PASSIVE optical networks (PONs) are poised for worldwide deployment for fiber-to-the-home. Efficient monitoring technology for high capacity networks is still missing [1]–[4]. In [5], we applied a modified optical code-division-multiplexing (OCDM) scheme for centralized fiber fault monitoring, proposing a single U-band source (Intl. Telecommunication Union PON monitoring standard, 1625–1675 nm) and a one-dimensional (1-D) coding scheme of passive splitters/combiners (PSC) or a multiple fiber Bragg grating (MFBG).

In [6], we simulated the system signal-to-noise ratio (SNR) for both broadband source (BBS) and laser sources using OCDM techniques. Both sources are limited by beat noise (BN) due to beating among the multiplicity of OCDM pulses contributing to the autocorrelation peak and falling in the detection window. By exploiting an extremely wide bandwidth (available in the U-band), the BBS can reduce the impact of both the limiting BN and its own inherent intensity noise, at the expense of poor spectral efficiency. For this reason, BBS were found to outperform coherent sources.

These studies, however, assumed the BBS pulse did not suffer any dispersion. The use of dispersion compensation increases cost and complexity and should be avoided, difficult to achieve when relying on an extremely wide (~8-nm) bandwidth. For example, consider dispersion of 20 ps/nm · km at $\lambda = 1650$ nm [1], and a 20-km feeder (40 km round-trip). A BBS with 8-nm bandwidth will lead to a 1-ns pulse becoming 6.40 ns wide.

Manuscript received May 23, 2008; revised August 26, 2008. First published October 31, 2008; current version published December 12, 2008.

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Digital Object Identifier 10.1109/LPT.2008.2006062

To reduce overall system cost by avoiding dispersion compensation, we seek a solution that reduces the limiting BN when using laser sources (readily available in the U-band). For instance, when using two-dimensional (2-D) coding, the number of pulses being correlated is reduced, reducing BN. Two-dimensional coding increases the cost per household of monitoring, as the client side encoders must be wavelength-selective, and thus more complex and more costly [7]. In order to remedy the BN problem of a laser-based 1-D coding, we introduce in this letter a new encoding/decoding architecture that combines the 1-D/2-D coding principles. Hybrid 1-D/2-D can be used for any OCDM system; however, in this letter we focus on the PON monitoring application. We show via simulation that our solution allows the monitoring of 64 customer PON with acceptable SNR $\geq$ 9 dB, while maintaining low cost per distribution-drop fiber (DDF).

II. Hybrid 1-D/2-D Coding Scheme

A. BN in 1-D Coding

All OCDM systems, and particularly 1-D time-coding, suffer greatly from BN. Beating occurs when we detect multiple pulses having center frequencies separated by less than the electrical bandwidth of the receiver. Pulses originate from the desired user (autocorrelation peak) and interference (nonzero cross-correlation). The total BN power, $\sigma^2_{\mathrm{BN},1-\mathrm{D}}$, is composed of three terms: signal-to-signal beating (SSB), signal-to-interference beating (SIB), and interference-to-interference beating (IIB) with respective powers σ^2_{SSB}, σ^2_{SIB}, and σ^2_{IIB}. We have

$$\sigma^2_{\mathrm{BN},1-\mathrm{D}} = \sigma^2_{\mathrm{SSB}} + \sigma^2_{\mathrm{SIB}} + \sigma^2_{\mathrm{IIB}}. \quad (1)$$

Desired pulses contributing to the auto-correlation peak (SSB) limit the performance even when no interference (no SIB and IIB) exists. Equation (1) is usually dominated by the SSB term, i.e., $\sigma^2_{\mathrm{BN},1-\mathrm{D}} = \sigma^2_{\mathrm{SSB}}$. In order to alleviate the BN, 2-D (wavelength-time coding) can be applied [7]. This solution completely removes the SSB term ($\sigma^2_{\mathrm{SSB}} = 0$) and reduces the average power of SIB and IIB [8]. While exhibiting good performance, this technique is quite expensive due to the high number of coding mirrors (CMs), i.e., fiber Bragg gratings (FBGs) at different wavelengths, required at the encoders [5], [6].

B. Principles of Hybrid 1-D/2-D Coding Monitoring

We propose a novel and cost-effective coding scheme we call hybrid 1-D/2-D. This combines advantages from each technique: the low cost of 1-D coding (at the customer end) and the BN mitigation capability of 2-D coding at the central office (CO). In addition, our solution does not modify existing PON

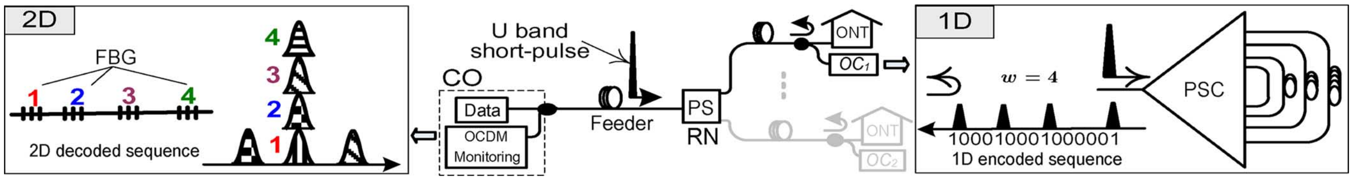

Fig. 1. Hybrid 1-D/2-D-OCDM for fiber fault monitoring in PON.

network infrastructure, and concentrates complexity at the CO, amortizing the cost over all customers.

Our new monitoring concept exploits three key elements seen in Fig. 1. First, our optical source is required to be multiwavelength, consisting of a comb of U-band lasers at the CO. Second, CMs placed at the client fiber terminations remain PSC, the least expensive 1-D encoders, as in [6]. Third, at the CO innovative 2-D decoding over the reflected sequence uses 2-D MFBG decoders.

The monitoring equipment located at the CO sends a comb of w (code weight) pulsed wavelengths simultaneously to the network. The 1-D encoder reflects back w replicas of the 1-D encoded sequence, each on a different wavelength. At the CO, the decoder is a standard MFBG 2-D decoder (see Fig. 1) that superposes w desired pulses selected from the w^2 (wavelength/time) returned pulses; only one pulse per wavelength is selected. Using an MFBG decoder at the CO has two advantages with respect to using a PSC decoder: 1) the total loss is reduced by w^2, and 2) MFBG wavelength selectivity effectively eliminates BN from pulses returned by the desired CM, i.e., SSB, by disallowing same-wavelength pulses in the autocorrelation peak (Fig. 1).

C. *BN Mitigation of Hybrid 1-D/2-D Scheme*

Fig. 2(a) shows the spectral distribution of the BN in a standard 1-D scheme, which is composed of two power peaks. The higher peak is due to beating between the same-wavelength, desired pulses, i.e., SSB. The lower peak is due to interference contribution, i.e., SIB and IIB. Recall that our 1-D/2-D autocorrelation peak is formed from pulses on different wavelengths. We see in Fig. 2(b) that this shifts the SSB spectrum out of the electric band $[-B_e, B_e]$, i.e., away from the desired DC autocorrelation peak spectrum [delta function in Fig. 2(a) and (b)], so $\sigma^2_{\mathrm{SSB}} = 0$.

As in standard 2-D coding, not only is the beating among desired pulses eliminated, but the interference contribution is also reduced by a factor equal to the code weight w [8]. In our case, this reduction applies to both SIB and IIB terms in (1). The total BN power for hybrid 1-D/2-D, i.e., $\sigma^2_{\mathrm{BN,H}}$ is

$$\sigma^2_{\mathrm{BN,H}} = \frac{\sigma^2_{\mathrm{SIB}} + \sigma^2_{\mathrm{IIB}}}{w}. \tag{2}$$

Usually IIB has a negligible power compared to SIB, i.e., $\sigma^2_{\mathrm{IIB}} \ll \sigma^2_{\mathrm{SIB}}$. So we have $\sigma^2_{\mathrm{BN,H}} \approx \sigma^2_{\mathrm{SIB}}/w$. Comparing (1) and (2) shows a significant reduction in the total BN power by removing the SSB term. Increasing the interference directly increases the total BN power per (2). Note that in (1) this dependency is negligible.

In [6], we showed that interference in our system varies with the geographical density of customers. Decreasing the geographic client density directly decreases the BN power in (2); in (1) this effect is more diluted, as the SSB term dominates. For our simulations, we have assumed a fixed coverage area of one square kilometer. An increase in network size, therefore, corresponds to greater client density, and greater interference. The dependence on geographic density for 1-D and 2-D coding is analyzed in [6] and can be applied in a straight-forward manner to the 1-D/2-D hybrid.

III. Performance Analysis

A. *Signal-to-Noise Ratio*

We define the SNR as

$$\mathrm{SNR} = \frac{\mu^2_{\mathrm{SIG}}}{\sigma^2_{\mathrm{N}}} = \frac{\mu^2_{\mathrm{SIG}}}{\sigma^2_{\mathrm{TH}} + \sigma^2_{\mathrm{D}} + \sigma^2_{\mathrm{SH}} + \sigma^2_{\mathrm{BN}} + \sigma^2_{\mathrm{RIN}}} \tag{3}$$

where the index TH is used for thermal noise (spectral density 0.1 pA $\cdot$ Hz$^{-0.5}$ assumed), D for dark current noise (average current 160 nA), SH for shot noise, BN for beat noise, RIN for relative intensity noise of the BBS, and μ_{SIG} is the autocorrelation peak. We consider a laser source with 10-MHz linewidth and a BBS with 1-THz bandwidth. We assume perfect dispersion compensation as in [6]. The pulsewidth is 1 ns, the pulse power is 4 dBm, an avalanche photodiode (gain $= 150$, excess noise factor $= 2.14$) is assumed, and we use an aggregate excess loss of 5 dB for splicing, connectors, etc. We considered a 20-km feeder fiber between the CO and the remote node (RN) in Fig. 1, and a uniform radial distribution for the distance between the ONTs and the RN in Fig. 1 over a fixed 1-km^2 coverage area [6]. The status (healthy or faulty) of the client fiber under consideration is modeled by a Bernoulli random variable with 0.99 probability of being healthy. We use 1-D codes defined by $w = 4$, F, $\lambda_a = \lambda_c = 1$; respectively, code weight, the code length (a function of the number of customers or network size), weight, and maximum out-of-phase auto, and cross-correlation [5], [6].

Fig. 3 presents simulation results of the SNR of our proposed hybrid 1-D/2-D coding scheme as compared to 1-D scheme using BBS (1-D-BBS).[1] While for 1-D-BBS BN power is dominated by SSB in (1), for the hybrid scheme, BN is dominated by the SIB term [see (2)]. For high network sizes, i.e., large numbers of clients, 1-D-BBS is dominated by shot noise, while the hybrid scheme is BN limited. Per Fig. 3, our proposed monitoring method allows up to a 64 customer network to be monitored with an SNR $= 9.1$ dB.

While providing better performance, our hybrid scheme is also spectrally efficient, using only a small portion of the monitoring band. Using partitioning the monitoring U-band, we can increase the network capacity that can be monitored [6]. The system SNR can be further improved by averaging techniques widely used in optical time domain reflectometry [9]; Fig. 3 uses a single trace, no averaging. This plot is for a 1-km^2 coverage

[1]Curves in [6] erroneously diminished the SN contribution; this error is corrected in results presented in Fig. 3.

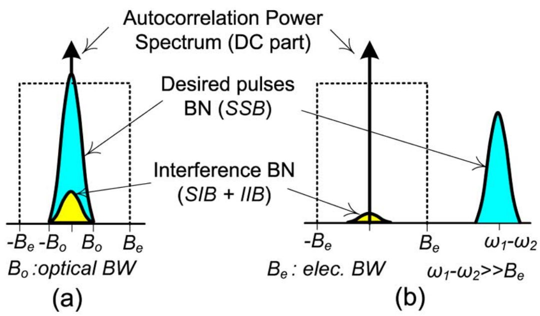

Fig. 2. Hybrid 1-D/2-D: (a) BN power spectrum of 1-D, and (b) BN power spectrum of hybrid 1-D/2-D; DC part of interference is neglected.

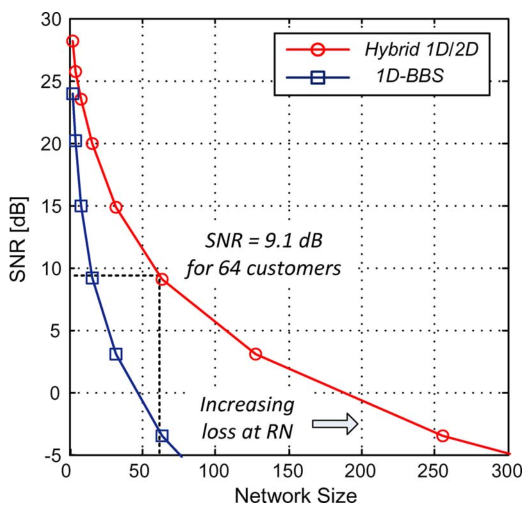

Fig. 3. SNR versus network size for 1-D-BBS (perfect dispersion compensation) and hybrid 1-D/2-D scheme.

area. Increasing the coverage area would decrease the client density, and improve the performance of our new hybrid scheme [6], [9].

B. False-Alarm and Detection Probabilities (P_{FA} and P_D)

Any CO error in the estimation of the DDF status results in a nonnegligible operational expenses. Declaring a fiber fault when none exists results in an expensive and unnecessary truck-roll of complex fiber-optic equipment. Alternately, CO failure to detect a fault in a DDF due to a noisy measurement leads to customer dissatisfaction and complaints. In order to better evaluate the performance of our monitoring system to detect DDF status, we examine the false-alarm and detection probabilities of healthy channels, as is done in radar applications [10].

By definition the false-alarm probability, $P_{\rm FA}$ is the probability of declaring a DDF healthy when it is faulty. The detection probability $P_{\rm D}$ is the probability of correctly declaring the DDF healthy. We investigate the receiver operating characteristic (ROC), i.e., a plot of $P_{\rm D}$ versus $P_{\rm FA}$ for our monitoring system, assuming the total noise to be Gaussian. The same system parameters as those of Section III-A are used. The ROC of our hybrid 1-D/2-D scheme is presented in Fig. 4 for different network capacities. These curves shows the trade-off of the network capacity against $P_{\rm D}$ and $P_{\rm FA}$. For instance, at 64 customers, the detection probability is very high ($P_{\rm D} = 0.991$), while preserving false-alarm rate as small as $P_{\rm FA} = 10^{-5}$. As the capacity increases, very small $P_{\rm FA}$ imposes small $P_{\rm D}$.

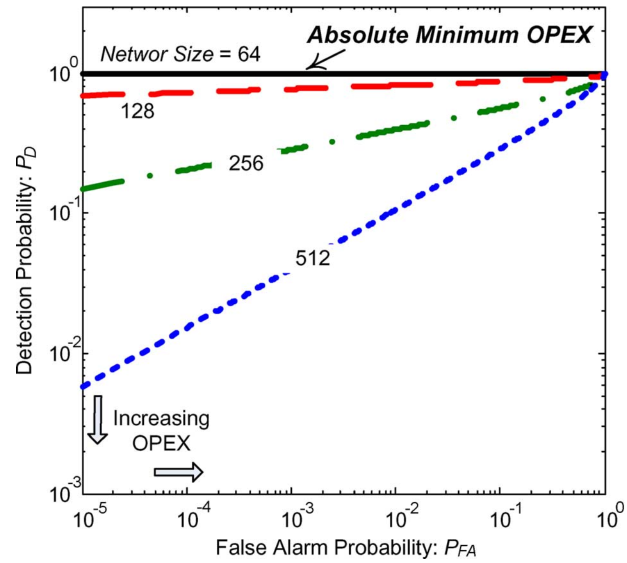

Fig. 4. Hybrid 1-D/2-D ROC for different network sizes.

IV. Conclusion

We proposed a new hybrid 1-D/2-D coding scheme for fiber fault monitoring in PON. This monitoring scheme is robust to dispersion, low in cost, and high in performance. We demonstrated that mixing 1-D and 2-D elements and characteristics is effective in mitigating the BN limiting 1-D performance. Simulations show that up to 64 customers can be monitored with $\rm SNR = 9.1$ dB.

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