Phase-Induced Intensity Noise Reduction with Improved Group Velocity Dispersion Tolerance in SAC-OCDMA Systems

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***Abstract*—The demand for efficient optical communication systems has fuelled considerable research in developing techniques for eradicating phase-induced intensity noise (PIIN) in spectral-amplitude coding optical code-division multiple-access (SAC-OCDMA). This paper investigates the use of modified-AND subtraction detection technique to mitigate PIIN in SAC-OCDMA systems. The simulation results show that the modified-AND subtraction detection demonstrates better performance over the conventional AND detection approach. Furthermore, we have found that, from a transmission length of 40 km onwards, group velocity dispersion (GVD) degrades SAC-OCDMA system performance apparently. Dispersion compensating fiber (DCF) is used to lessen the influence of GVD caused by single mode fiber (SMF).**

Keywords—optical code-division multiple-access (OCDMA), spectral-amplitude coding (SAC), modified-AND subtraction detection, phase-induced intensity noise (PIIN), group velocity dispersion (GVD).

I. INTRODUCTION

Over the last decade, there has been immense interest in optical code-division multiple-access (OCDMA) for its ability to support asynchronous access, bursty traffic, and differentiated quality-of-service (QoS) [1–3]. Nonetheless, the main disadvantages of conventional OCDMA systems are that the performance and capacity are limited by multiple-access interference (MAI) [4, 5]. Spectral-amplitude coding (SAC) is an OCDMA technique in which the spectrum of an incoherent broadband source is amplitude-encoded. In SAC systems, MAI is suppressed using subtraction detection techniques and fixed in-phase cross-correlation code sequences [6, 7]. However, the performance is still limited by PIIN [8, 9]. This noise is due to spontaneous emission of the broadband source, and its effect is proportional to the power of the generated photocurrent [10]. Thus, the summation of different users' signals at the receiver's end fluctuates in intensity, which increases the variance of the received signal [11].

Previous studies have used various techniques to reduce PIIN in SAC-OCDMA systems. Some researchers have reduced the number of overlaps between code signatures to minimize the in-phase cross-correlation. Others have attempted different approaches in solving the problem, such as using saturated semiconductor optical amplifiers (SOA) in the noise-cleaning process [12, 13]. Newly, the authors have proposed the modified-AND subtraction detection technique to overcome the impact of PIIN and MAI in incoherent SAC-OCDMA systems by dividing the spectrum of the utilized code sequences at the decoder branch [14].

However, PIIN is not the only restriction when implementing SAC-OCDMA optical fiber systems. Dispersion, especially GVD, is another major contributing factor to performance depreciation of SAC-OCDMA systems [15]. This depreciation comes from GVD influences include peak power reduction and pulse broadening of the optical signals and the time skewing impact that result from the difference between the group velocities of different wavelengths in SAC-OCDMA systems [15, 16]. Hence, observing the expected effect of GVD in addition to PIIN is important.

Modified double-weight (MDW) codes are utilized as the signature codes for SAC-OCDMA systems [17]. The MDW code has a unity cross-correlation with variable weights greater than two. For example, for a weight of four (w = 4), the code length is:

$$N = 3K + \frac{8}{3}\left[\sin\left(\frac{K\pi}{3}\right)\right]^2$$

(1)

where N is the code length and K is the number of users. Table I presents an example with six users of the MDW code. This study has been carried out through simulations using OptiSystem software (Version 9.0) from *optiwave*^{TM}, which considers all practical effects of fiber nonlinearities, dispersion, attenuation, receiver thermal noise, and dark current shot noise. Following the Introduction, the work is structured as follows. Section 2 provides a detailed explanation of the modified-AND subtraction detection technique. Next, in Section 3 we present the descriptions of the simulation experiments for SAC-OCDMA system. In Section 4, the results are presented and discussed. Finally, conclusions of the paper are made based on the findings in Section 5.

TABLE I
MDW code words with w = 4, N = 18 for 6 users.

User		Code words
K_1	=	{ 1 1 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 }
K_2	=	{ 0 1 1 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 }
K_3	=	{ 0 0 0 0 1 1 0 1 1 0 0 0 0 0 0 0 0 0 }
K_4	=	{ 0 0 0 0 0 0 0 0 0 1 1 0 1 1 0 0 0 0 }
K_5	=	{ 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 1 1 0 }
K_6	=	{ 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 0 1 1 }

II. MODIFIED-AND SUBTRACTION DETECTION

The SAC-OCDMA receiver diagram of this technique is shown in Fig. 1 [14]. The received optical signal is split by splitter 1 into two parts, one to the upper decoding branches and the other to the AND decoder through an attenuator. The attenuator ensures that the interference signal has an equivalent power incident on each photo-detector in the case of an inactive user. The decoder filters are placed in a parallel configuration. This structure divides the spectrum of the decoded signals. Take note that both splitters (splitter 1 and splitter 2) and the attenuator could be replaced by a single coupler with an appropriate coupling ratio in order to get a more cost-effective receiver. The decoder has a spectral response matched to the active user, whereas the AND decoder has overlapped bins from different interferers. These overlapped bins can be represented mathematically by AND operation between the active user and interferers [18]. This technique can be performed using the inexpensive fiber Bragg-gratings (FBGs) to decode the received signal because of their low insertion losses, good spectral resolution, small size, and light weight [19]. The photo-detector is composed of two photodiodes (PD and *s*-PD) which are connected electrically in opposition. The output signal is proportional to the power difference of the two optical inputs. In the presence of an interferer, the difference between the two signals is cancelled out. The output signal is then low-pass filtered to reduce the out-of-band high-frequency noise. After the decision circuit, the original data is restored.

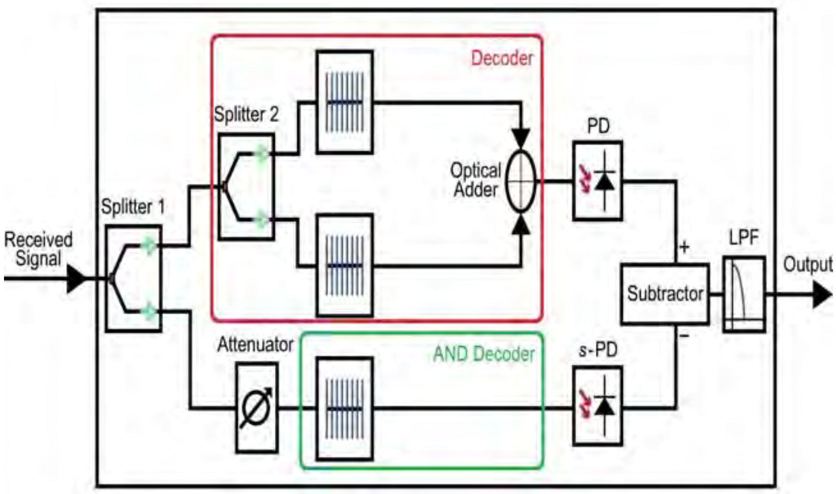
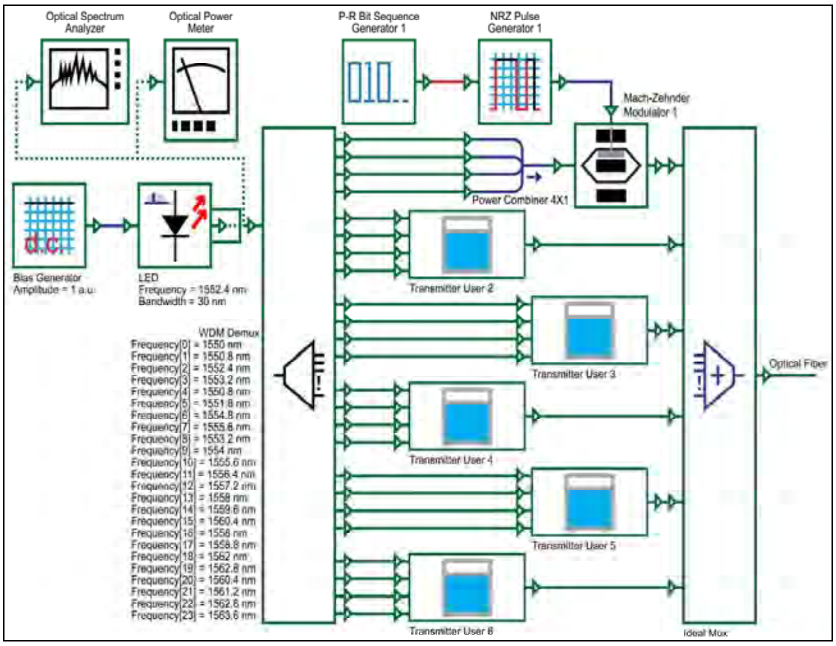


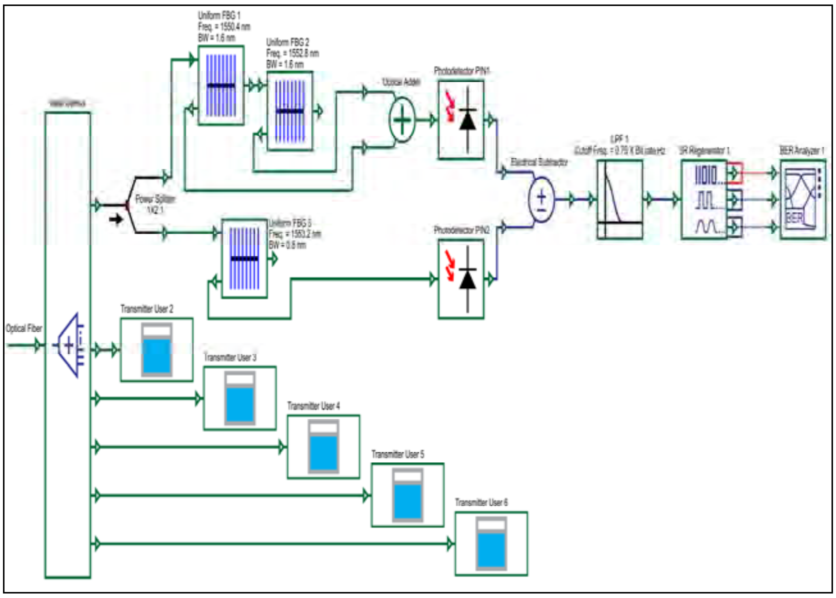
Fig.1. Implementation of modified-AND subtraction detection technique.

III. SAC-OCDMA SIMULATION SETUP

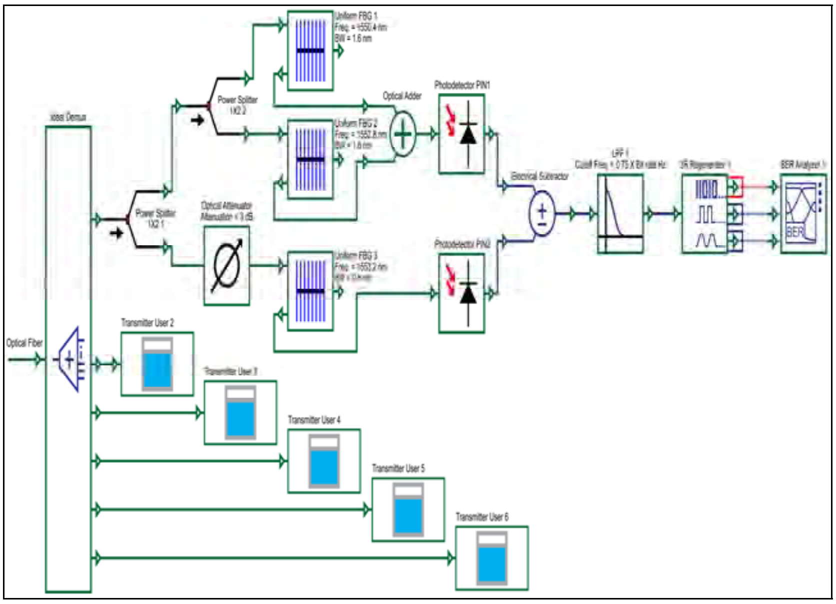
The simulation of incoherent SAC-OCDMA systems has been conducted using OptiSystem software, which is widely used in optical fiber simulations. A schematic diagram for six users is depicted in Fig. 2 using MDW code (w=4). Tests were carried out by one broadband light-emitting diode (LED) sliced into 24 wavelengths using WDM demultiplexer to generate the OCDMA codes. The information signals are generated from the pseudo random bit generator with the non-return-to-zero (NRZ) line coding before being modulated with the codes using an external Mach Zehnder modulator. Each chip has a spectral width of 0.8 nm. The attenuation and the dispersion coefficients of SMF at a wavelength of 1550 nm are 0.25 dB/km and 18 ps/km/nm respectively according to the ITU-T G.652 standard. Nonlinear effects were specified as close to typical industrial values as possible to simulate the real environment. Further, it will be assumed that the transmitted power of the light source is limited. However, to overcome this limitation an optical amplifier with gain of 20 dB is used. The noise generated at the receivers was set as random and totally uncorrelated. The dark current value was set at 5 nA, and the thermal noise coefficient was 1.8×10^{-23} W/Hz for each of the photo-diodes at the detection part.



(a)



(b)



(c)

Fig. 2. Simulation setup of SAC-OCDMA; (a) Transmitter; (b) Receiver based on AND subtraction detection; (c) Receiver based on modified-AND subtraction detection.

IV. Results and Discussion

In this section, the performance of SAC-OCDMA systems is assessed by referring to the bit-error rate (BER) values and eye diagrams. The dispersion is compensated by employing a DCF with the original fiber. Such fiber can be designed to have a negative GVD value at 1550 nm and is usually used to compensate the accumulated dispersion of a conventional SMF-based transmission link. The length of DCF used in the simulation is computed from

$$L_{DCF} = -\frac{L_{SMF} D_{SMF}}{D_{DCF}} \tag{2}$$

where L and D denote the fiber length and GVD, respectively. The subscripts *SMF* and *DCF* stand for the fiber type [20]. The D_{DCF} value used in the simulation is -90 ps/km/nm.

Fig. 3 compares the effects of incorporating DCF on the variation of BER values with respect to transmission lengths for the AND as well as modified-AND detection schemes at 1.25Gbps and 2.5Gbps. The fiber length L in Fig. 3 refers to the total fiber link length

$$L = L_{SMF} + L_{DCF} \tag{3}$$

Interestingly, the modified-AND subtraction detection scheme demonstrates better performance over the conventional AND detection approach and gives the advantage of increasing the length of the transmission link without affecting the QoS. The advantage of modified-AND detection is mainly because of its ability to assuage both PIIN and MAI. BER samples without DCF are used as references for comparison. At 1.25 Gbps, for both detection schemes, it is evident that the DCF clearly enhances the BER at all fiber lengths. Thus, after using the modified-AND subtraction detection with DCF, the system achieves the best BER at a data rate of 1.25 Gbps. Further, the modified-AND detection scheme shows a more significant improvement in the BER compared to the AND detection scheme with the use of DCF, approximately from a transmission length of 40 km and up. Fig. 4 compares eye diagrams for the AND detection scheme, with and without DCF, at 40 km fiber lengths and data rate of 1.25 Gbps. The eye diagrams clearly depict that DCF gives better performance, with the eye diagram having a large opening. Fig. 5 shows typical eye diagrams for the modified-AND detection technique, with and without DCF, at 40 km fiber lengths and data rate of 1.25 Gbps. The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise. Moreover, at 2.5 Gbps, the modified-AND detection scheme with the use of a DCF improves the BER to an acceptable value in the order of 10^{-10} for fiber lengths under 20 km. On the contrary, at 2.5 Gbps, the AND detection scheme does not achieve the minimum acceptable BER, even with DCF.

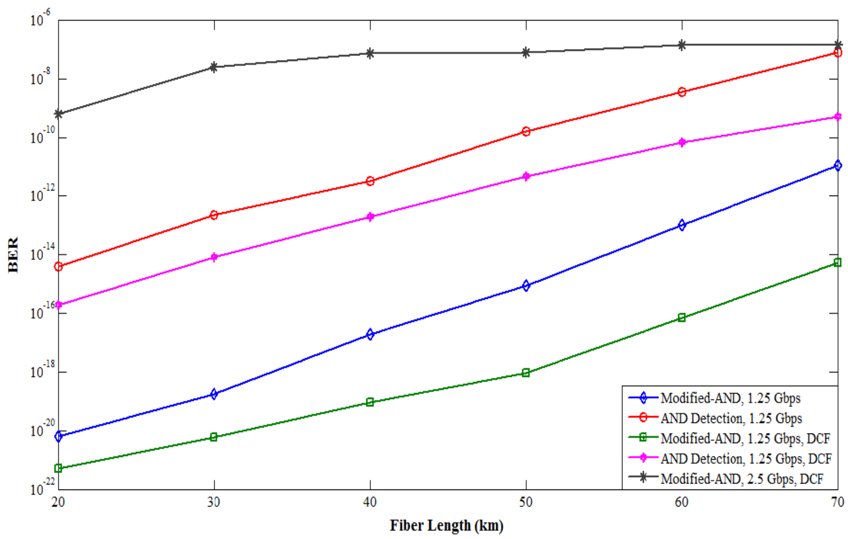


Fig. 3. BER versus fiber length for AND as well as modified-AND detections with and without dispersion compensation.

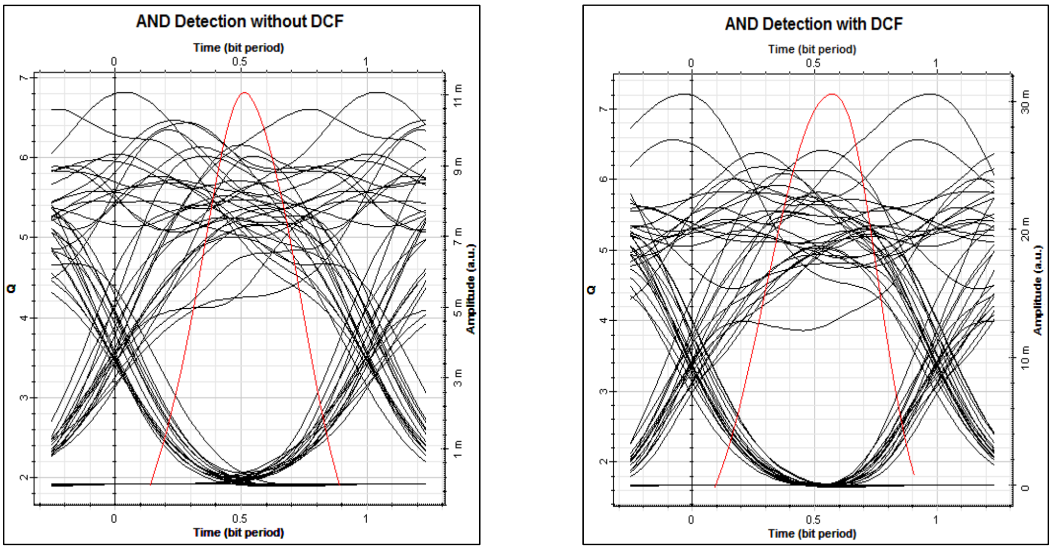


Fig. 4. Eye diagrams for MDW code using AND subtraction detection with and without dispersion compensation.

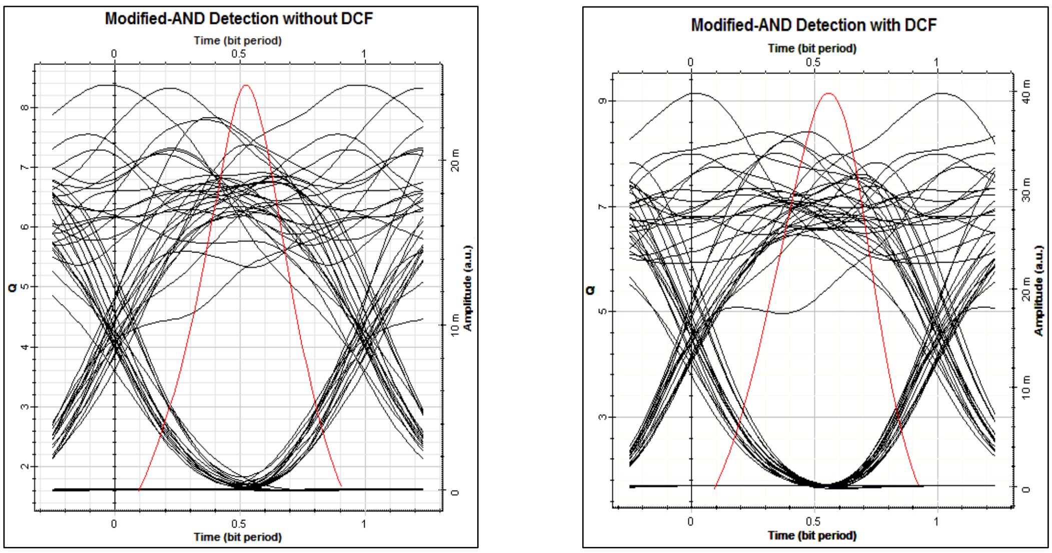


Fig. 5. Eye diagrams for MDW code using modified-AND subtraction detection with and without dispersion compensation.

V. CONCLUSIONS

The performance of different detection schemes for SAC-OCDMA systems is compared. Simulations were carried out by slicing one LED to support six active users. According to the results, the modified-AND detection technique shows significant performance enhancement over the AND detection technique. Its usefulness is mainly because of its ability to alleviate both PIIN and MAI. The GVD is also an important system limitation for long transmission distance which must be reduced. Results confirmed a noticeable improvement in the system performance which indicates that the impact of GVD is effectively compensated using DCF. Thus, it is concluded that the modified-AND detection technique may be a useful choice for future optical access networks.

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