Experimental Demonstration of Bipolar Optical CDMA System Using a Balanced Transmitter and Complementary Spectral Encoding

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***Abstract*—We demonstrate a novel balanced differential optical transmitter for spectrally encoded optical code-division multiple-access (CDMA) systems. The proposed structure is suitable for making optical signaling bipolar using complementary spectral encoding. An optical CDMA link with a pair of programmable transmitter and receiver is tested at the OC-3 transmission speed (155 Mb/s) for single-channel transmission. Unmatched code rejection is also demonstrated in this work.**

***Index Terms*—Balanced receiver, balanced transmitter, bipolar signaling, optical CDMA, spectral encoding.**

OPTICAL CODE-DIVISION multiple-access (CDMA) was first conceived as a multiple access protocol in a local area network (LAN) environment [1], [2]. In a LAN environment where the traffic is usually bursty, an efficient multiple-access protocol that allows users to access the network asynchronously at all times is important. By using optical processing, one can alleviate the amount of electronic multiplexing bottleneck and overhead. Besides, CDMA systems also offer a security advantage over other multiple access systems.

Most of the proposed optical CDMA systems [1]–[4] employ coherent or noncoherent encoding of ultrashort optical pulses. The coherent approach [3] involves complicated phase and polarization synchronization and is difficult to implement. The noncoherent approach [1], [2], [4] uses delay line encoders and pseudoorthogonal intensity codes which can never achieve true orthogonality. To reduce crosstalk, these codes are designed with long code lengths and small code weight which reduces the spectral efficiency of the system.

Spectrally encoded optical CDMA first appeared in [5]. It is known that by employing complementary spectral encoding and balanced detection [6], one can achieve complete bipolarity and true orthogonality. Moreover bipolar signaling has a 3-dB signal to noise advantage over on–off keying systems.

In this letter, we propose and experimentally demonstrate a bipolar spectrally encoded optical CDMA system using a novel balanced transmitter, which employs an array of optical switches to manipulate the optical code signature, hence offering full system configurability and the possibility of fast code hopping and enhanced security. The added security in the physical layer can be useful for high bandwidth real time secure data transmissions such as voice and motion picture systems where encryption delay is critical.

The schematic diagram of the proposed system is shown in Fig. 1(a). The double balanced transmitter comprises two serially-connected broadband optical sources such as super-luminescent light-emitting diodes (LED), or the spontaneous emission output from erbium-doped fibers pumped into super-luminescent mode. Alternatively, multiwavelength laser sources could also be used, as will be demonstrated later. In either case, an intensity encoder [Fig. 1(b)] is employed to selectively transmit or block certain spectral components of the balanced transmitter output. Two identical wavelength-division-multiplexed (WDM) demultiplexers are used to disperse the outputs from the balanced transmitter. An array of 2 × 2 switches control the transmission of individual wavelength components from either of the two broad-band optical sources. When a switch b_i in the array is in the BAR (or CROSS) state, wavelength λ_i from the upper (or lower) optical source of the balanced transmitter is transmitted. The states of the switches, $\{b_1, b_2, \cdots, b_n\}$, thus define the encoded spectrum at the output WDM multiplexer. Data modulation is achieved by direct modulation of the balanced optical sources, generating the direct and complementary encoded output spectra defined by $\{b_1, b_2, \cdots, b_n\}$ for 0 and 1 bit. The encoded spectra from various transmitters are broadcast to the receivers through a star coupler. Each receiver consists of a decoder and a balanced detector. The decoder [Fig. 1(c)] has a similar structure as the encoder, but provides the reciprocal optical path. The same encoding switch array is used for decoding. Two photodetectors connected in a balanced fashion are used to detect the difference signal between the complementary outputs of the two WDM multiplexers at the decoder. Spectral components corresponding to the direct (or complementary) encoded spectrum of the matched transmitter are combined at the upper (or lower) photodetector. Therefore, for a matched channel, the direct and complementary encoded spectra produce a $+1$ and -1, respectively, at the output of the balanced detector. However, a signal from an unmatched transmitter results in the received spectrum equally split between the two complementary spectral outputs of the decoder, generating zero output at the balanced detector.

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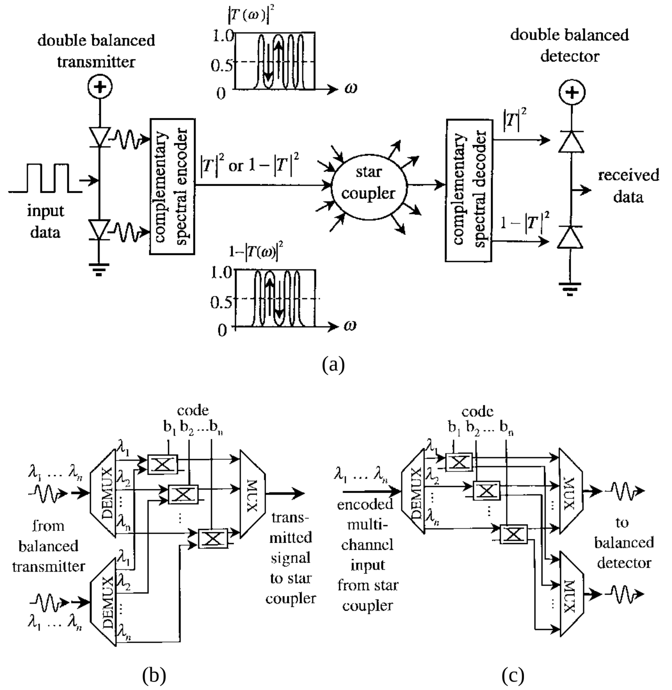

Fig. 1. (a) System structure of bipolar spectrally encoded optical CDMA. The complementary spectra produced by the spectral filter, $|T|^2$ and $\overline{|T|^2}$, represent the complementary intensity transfer functions of the spectral filter outputs. A balanced broad-band source is spectrally encoded and received by a balanced receiver. Modulation is performed by alternating between the two input sources electrically. (b) Details of the complementary spectral encoder. (c) Details of the complementary spectral decoder.

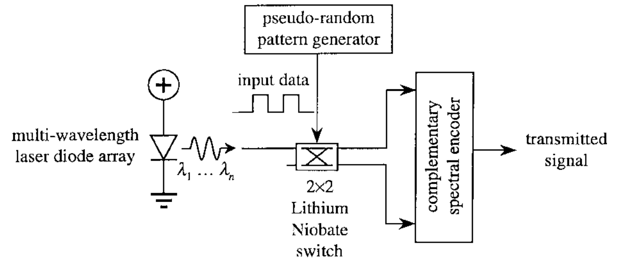

Fig. 2. Experimental set-up used to emulate the balanced transmitter. A multiwavelength laser diode array output is switched between the two input ports of the encoder using an electrooptic 2×2 switch.

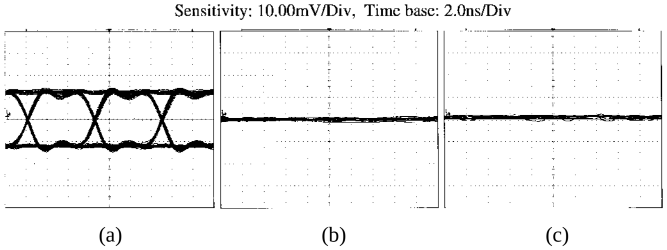

Fig. 3. Eye diagrams obtained for the (1010) encoding when the receiver is set to decode. (a) Matched code (1010). (b) Unmatched code (1100). (c) Unmatched code (1001). Error-free transmission is obtained for the matched code. Unmatched codes are rejected.

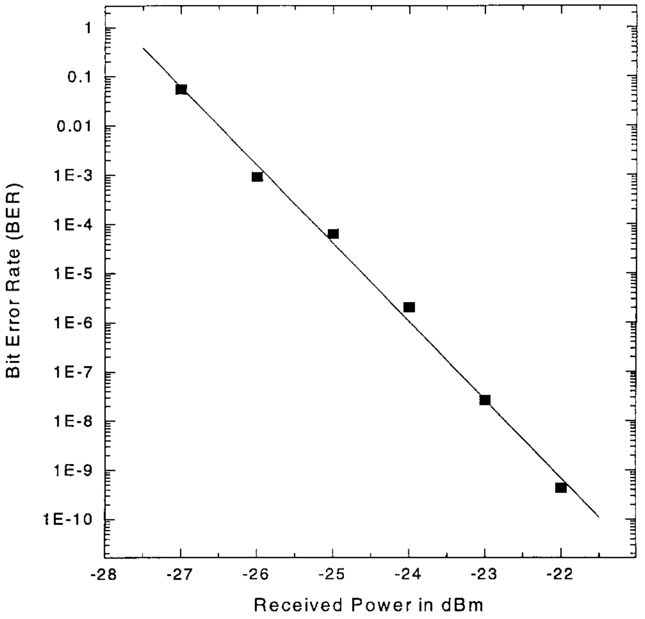

Fig. 4. The BER plot against the received power at 155-Mb/s speed for the matched transmitter and receiver pair that uses the code (1010).

To demonstrate the bipolar spectrally encoded optical CDMA system, an experimental prototype is constructed. In this demonstration, a four-wavelength laser diode array is employed as the broadband optical source. The four wavelengths are $\lambda_1 = 1542$, $\lambda_2 = 1547$, $\lambda_3 = 1552$, and $\lambda_4 = 1557$ nm, correspond to the passband peaks of the four-wavelength WDM multiplexers used in the setup. In order to emulate the balanced transmitter, a 2×2 electrooptic switch is employed to route the laser diode array output between the two input ports of the encoder (Fig. 2). The 2×2 optical switch is driven by a $2^{15}-1$ pseudorandom pattern at 155 Mb/s which serves as the input data. By programming the switch array within the encoder, 4×4 Hadamard matrix codes that contain rows of (1111), (1010), (1100), and (1001) are obtained. Each row corresponds to an encoded spectrum. For example, the (1010) row represents the situation of setting the 2×2 switches corresponding to λ_1 and λ_3 to the BAR state and others to the CROSS state. The (1111) row corresponds to on–off keying of all the wavelengths and is dropped due to lack of encoding. The decoded signal is received by a commercial balanced photodetector, followed by an amplifier and a low-pass filter to remove the out-of-band high-frequency noise.

Fig. 3(a) shows the eye diagram of an error-free transmission at 155 Mb/s with both the encoder and decoder set to (1010). The rejection of the unmatched spectrum at (1100) and (1001) by the decoder are also shown in Fig. 3(b) and (c). For both unmatched spectra, the output from the balanced detector is almost zero and a rejection ratio of better than 20 dB is achieved. The bit-error rate (BER) for the matched spectrum of (1010) is plotted against the received optical power in Fig. 4. A 10^{-9} BER is obtained at a -22.25-dBm received optical power. The measured BER is mainly limited by the noise of the amplifier, which has a noise equivalent power of 40 pW/$\sqrt{\text{Hz}}$.

Fast code hopping in nanoseconds can be realized by using electrooptic switches in the encoder and decoder for high-security applications and optical packet switching. The uniformity of the extinction ratios within the switch array is a potential concern to channel crosstalk. Under the scheme of balanced detection, nonuniform extinction ratios of the switches may introduce a finite output for unmatched channels as crosstalk. However, as the number of wavelengths increases, this crosstalk is reduced due to statistical averaging. The number of wavelengths also determines the size of code famility, system capacity and security. Current state-of-the-art monolithic multiwavelength distributed feedback laser array provides 40 wavelengths [7]. Alternatively, mode-locked laser, which has been demonstrated with 206 wavelengths [8] could also be used. Free-space diffraction gratings and arrayed waveguide WDM multiplexer–demultiplexers (MUX–DEMUX) with more than 100 wavelengths are available [9]. With a moderate number of wavelengths, the security of the system can be improved by permuting the wavelengths first before an orthogonal encoding is imposed. Also, since each transmitter transmits energy for both 0 and 1 bit, demodulation cannot be done by simple amplitude detection. In the presence of multiple users transmitting asynchronously on the same channel, it is much more difficult to extract the information unless the correct code is used. Moreover, since each wavelength can be independently controlled, the producible code book can be very general and only limited by physical properties such as the available source bandwidth and the WDM MUX–DEMUX resolution, etc.

Dispersion is a limitation to CDMA systems which all use broadband sources. In CDMA systems using ultrashort pulses, successful decoding relies upon the reconstruction of the ultrashort pulses which occupy only a small fraction of the bit period. Especially for the coherent scheme [3], dispersion has to be carefully controlled to maintain the optical phase coherence among different spectral components. There are no necessary fancy ultrashort pulse sources in our proposed system. The encoder and decoder function as spectral intensity filters. The bit energy occupies the full bit period. The proposed system is therefore less vulnerable to dispersion problems. For example, if a 40-nm optical bandwidth is used for encoding and the channel speed is 1 Gb/s, the dispersion limited transmission distance is about 1 km that is adequate for typical LAN applications. The transmitter modulates at the data rate and the receiver uses direct detection, which is a mature technology. However, in systems using ultrashort pulses [3], clumsy nonlinear optical threshold detection schemes such as second-harmonic generations are required.

It can be shown that the spectrally encoded CDMA system outperforms spectrally sliced WDM systems when a broadband spontaneous emission source is used for multiple access [10]. This is because the spectrally encoded CDMA system makes use of the whole available spectrum and is therefore more power efficient. More importantly, it is known that in spectrally sliced WDM systems using spontaneous emission sources, excess intensity noise or speckle noise will limit the performance [11]. When the system is speckle noise limited, the signal-to-noise ratio does not depend on the received power but the ratio of the optical bandwidth to the data bandwidth. Because a wider spectrum is used in spectrally encoded CDMA, it helps to improve the speckle noise in a spontaneous emission source. Co-channel access by multiple users in a CDMA network will introduce interference to the desired channel because the receiver detects the signal energy from all users and rejects the unwanted channels. There are two fundamental interference mechanisms. The first one is due to the shot noise associated with the total detected optical power. The second one, which is more important, comes from the speckle noise generated by the beating of optical signals from independent users [12]. It also sets the ultimate supportable aggregate throughput. About 12 simultaneous active users can be supported at 1-Gb/s speed per channel for 10^{-9} BER in the speckle noise limit. The BER will degrade gracefully as more users become active.

In a LAN environment with limited span, most of the loss comes from the splitting loss in the star coupler and component insertion loss, which can be improved by better integration of the optical components and using optical amplifiers. In a conservative estimate, given 10-dBm transmitter power, −20-dBm receiver sensitivity, and 15-dB insertion loss in the encoder and decoder, a network with 100 users should be achievable by placing a 20-dB optical amplifier after the star coupler. A detailed performance evaluation of spectrally encoded CDMA systems will be given elsewhere.

In conclusion, we have demonstrated the first bipolar fiber optic CDMA system using complementary spectral encoding and a balanced transmitter. A proof-of-principle single channel transmission experiment at 155 Mb/s speed has been carried out. Unmatched channel rejection is also shown in the experiment. Such systems have the potential for secure optical LAN applications.

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