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## All-optical CDMA with bipolar codes

L. Nguyen, B. Aazhang and J.F. Young

*Indexing terms:* Code division multiple access, Optical communications

A method for the transmission and detection of bipolar sequences in a unipolar system is presented. It allows all-optical implementation, in noncoherent optical CDMA systems, of the bipolar codes that have been developed for the radio domain. A practical design is described that encodes the spectrum of a broadband optical source to support a large number of subscribers.

**System description:** There has been considerable interest in applying CDMA techniques developed in the radio domain to optical fibre LANs. Practically, a LAN must support a large pool of subscribers, not all of whom require access to the network at the same time. The bipolar codes of the radio domain, however, are generally thought to be inapplicable to noncoherent optical systems, which only detect and process the signal intensity. Various schemes that have been proposed [1, 2] require balanced/special codes, offset removal or electronic correlations [3] that preclude the general, all-optical, application of the bipolar codes. In this Letter we present a modulation and detection method that allows all-optical implementation of the bipolar codes and correlation detectors.

Consider a bipolar sequence  $x_n$  of period  $N$  that takes values from  $\{-1, 1\}$ ;  $x_n$  can be expressed as the difference of two unipolar sequences with the same period, say  $u_n$  and  $\bar{u}_n$  that take values from  $\{0, 1\}$ , where  $u_n$  is obtained from  $x_n$  by replacing each  $-1$  with 0 and  $\bar{u}_n$  is its binary complement. Similarly, let  $v_n$  be the unipolar sequence obtained from a bipolar sequence  $y_n$  of period  $N$ . Then the periodic and aperiodic crosscorrelation functions of  $x_n$  and  $y_n$  can be computed in terms of the unipolar crosscorrelation functions:

$$\theta_{x,y}(l) = [\theta_{u,v}(l) + \theta_{\bar{u},\bar{v}}(l)] - [\theta_{u,\bar{v}}(l) + \theta_{\bar{u},v}(l)] \quad (1)$$

$$C_{x,y}(l) = [C_{u,v}(l) + C_{\bar{u},\bar{v}}(l)] - [C_{u,\bar{v}}(l) + C_{\bar{u},v}(l)] \quad (2)$$

A CDMA scheme based on the above results is shown in Fig. 1. The data symbols are encoded by  $u_n$  and  $\bar{u}_n$  which ON/OFF modulate the signal source in two channels such that if, say, symbol '1' is transmitted, then  $u_n$  is on channel A and  $\bar{u}_n$  on B, and vice versa for '0'. The received signals are decoded according to eqns. 1 and 2 with the unipolar matched filters  $U(N-1-n)$  and  $\bar{U}(N-1-n)$ , where the codeword  $U$  corresponds to one period of  $u_n$ . The outputs of each of the two complementary correlator pairs are optically summed and photodetected. The two photodiodes are connected in a balanced configuration so that their outputs are subtracted. The result is lowpass-filtered and threshold-compared to zero to estimate the transmitted symbol. As the two correlator pairs are identical, a configuration that requires only one is feasible with an appropriate repetitive transmission, by which the symbols are Manchester-coded. The received signals are differentially decoded with one unipolar correlator pair and one photodetector, followed by a delay and a comparator. We note that a particular

case of the above general schemes, for which  $u_n = 1$ , is equivalent to the binary PPM or noncoherent FSK modulation system.

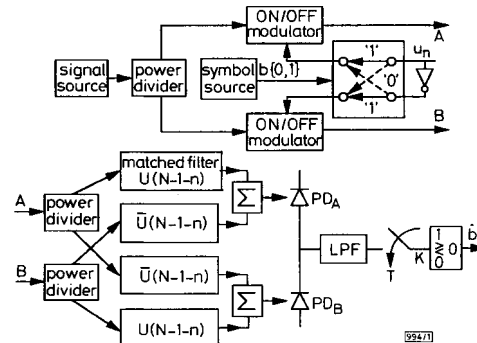


Fig. 1 Encoder and decoder block diagram

**Implementation:** All-optical implementations of the proposed scheme are practical with either time or spectral encoding methods. In time-encoded systems, the encoders are realised with a short-pulsed source and fibre tapped-delay lines [4]. The channels can be distinguished with two wavelengths, two orthogonal polarisations, or simply by time-multiplexing. Depending on the transmission method, the received signals are accordingly separated, and delayed if time-multiplexed, prior to the correlation operations. The unipolar correlators can be realised with fibre tapped-delay line filters that are matched to the codewords.

A spectral encoding method, however, offers several advantages because the temporal nature of the data symbols is largely decoupled from the spectral nature of the codes. This enables the system electronics to operate at the symbol rate while making full use of the source bandwidth. As spectral code correlations are synchronous, Walsh codes can be used to provide orthogonality between users. Moreover, if the code has small offset periodic autocorrelation values, its cyclic shifts can be assigned to different users. For example, the two-valued autocorrelation property of the  $m$ -sequence can result in a simplification of Fig. 1 and lead to the structure in [5]. In the case of the Gold or Kassami codes, all  $N$  cyclic shifts of each of the codewords can be used to give a code book of size  $N(N+2)$  or  $N^2[N+1]$ . This is very desirable in applications that must support a large pool of subscribers with bursty access to the network.

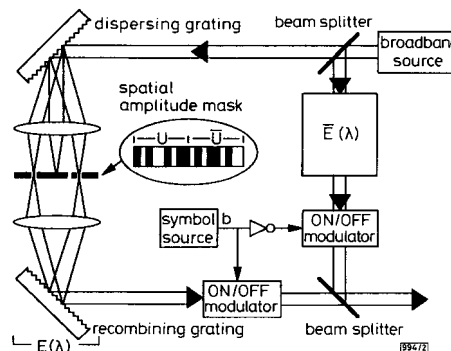


Fig. 2 Schematic diagram of spectral encoder

An illustration of an all-optical spectral encoder  $E(\lambda)$  is shown in Fig. 2. The spectrum of a broadband source is angularly dispersed by a grating and focused on to a spatial amplitude mask. The spectral bands, or chips, are selectively transmitted through the mask and recombined by another grating. The mask pattern represents the concatenated codewords words  $U \oplus \bar{U}$  of length  $2N$ . A second encoder  $E(\lambda)$  with the complement mask pattern encodes  $\bar{U} \oplus U$ . The decoders at the receiver are identical to the encoders, with the output beams coupled to the balanced photodetector pair. The two beams can also be generated with a single 2D mask by stacking the two mask patterns. Alternately, a single 1D

reflecting mask can be used to provide  $U \otimes \bar{U}$  in transmission and  $\bar{U} \otimes U$  in reflection. This configuration can be efficient because all of the spectral power is used.

The spectral encoding system with Walsh codes is analysed in terms of the signal/noise ratio of the decision statistics  $K$  at the comparator input. We model  $K$  as the difference of two independent random variables  $K_A$  and  $K_B$  that represent the photoelectron counts measured by the two photodetectors during the symbol interval  $T$ . Without loss of generality, let user 1 be the desired transmitter among the  $M$  simultaneously active users. The distributions of  $K_A$  and  $K_B$ , conditioned on the transmitted symbol of user 1, obey the Poisson probability mass function. Their conditional means are given by:

$$E[K_A|b=1] = E[K_B|b=0] = N\Lambda_1 T + 0.5N \sum_{j=2}^M \Lambda_j T + \Lambda_d T \quad (3)$$

$$E[K_A|b=0] = E[K_B|b=1] = 0.5N \sum_{j=2}^M \Lambda_j T + \Lambda_d T \quad (4)$$

where  $\Lambda_j$  is the spectral chip intensity of user  $j$  (assumed constant for each user) and  $\Lambda_d$  is the intensity of the photodetectors' dark currents (assumed equal). For shot-noise limited conditions, the signal/noise ratio of user 1 is

$$SNR = \frac{E^2[K]}{\sigma_K^2} = \frac{N\Lambda_1 T}{1 + 2\Lambda_d/\Lambda_1 + \sum_{j=2}^M \Lambda_j/\Lambda_1} \quad (5)$$

For equal chip intensities that are much larger than the dark currents,  $SNR \approx N\Lambda_1 T/M$ . In comparison, a spectrum-sliced WDMA system [6] that supports  $N$  users, each using two spectral chips for binary FSK, would require the same source bandwidth with  $SNR \approx \Lambda_1 T$ , which is  $N/M$  times worse. For example, if only half of the  $N$  orthogonal users are active at any one time, the SNR is improved by 3dB. The larger SNR is due to the efficient use of the source spectral power relative to spectrum-sliced WDMA.

An erbium-doped superfluorescent fibre source [7], pumped by a diode laser, can produce a few milliwatts of output power in a single spatial mode having almost 30nm of bandwidth at 1.55 $\mu$ m. Using reasonable grating sizes, an encoder having 256 spectral chips can be realised. This could support 128 orthogonal users using Walsh codes, or a pool of users that exceeds 16000 using Gold codes. Potentially, the encoder and decoder configuration described above could be fabricated as an integrated waveguide system, making it compact and practical.

**Conclusion:** We have presented a general modulation and detection method for bipolar codes in a unipolar system that is suitable for noncoherent optical CDMA applications. An all-optical spectral encoding design is described that uses the spectrum of a broadband optical source, and can accommodate a large pool of subscribers. Its SNR with Walsh codes exceeds that of a spectrum-sliced WDMA system with binary FSK due to efficient use of the source spectral power.

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## Demonstration of 205 km transmission of 35 GHz, 5ps pulses generated from a diode-driven, low-jitter, beat-signal to soliton train conversion source

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Indexing terms: Soliton transmission

The authors discuss the performance of a low-timing-jitter, diode-driven, Nd:YLF pumped 5ps, 30-40GHz soliton source based on beat-signal conversion in a dispersion-decreasing fibre. In addition, the first experimental demonstration is reported of long-distance (205km) propagation of such pulse streams in an amplified transmission line incorporating three amplifiers at 50 km amplifier spacing.

There has been considerable recent interest in the development of optical techniques for the generation of high-frequency soliton trains based on a nonlinear beat signal to soliton train conversion in dispersion-profiled fibre circuits (see, for example, [1-4]). The techniques offer advantages of ultrahigh-repetition rates, high pulse quality, and broad wavelength and repetition rate tunability. However, although impressive source demonstrations have been made, their practical applications to date have been limited, owing primarily to issues relating to timing jitter [3, 4], Brillouin scattering [2, 3] and difficulties in applying the techniques to repetition rate ranges <40GHz [1] to allow compatibility with state-of-the-art, high-data-rate electronics. In this Letter we report the development and performance of a diode-driven, ultralow jitter, 30-40GHz soliton source with potential for telecommunication applications. In addition, we report the results of pulse propagation measurements of 35GHz repetition rate, 5ps pulses over a 205km dispersion-shifted fibre (DSF) transmission line [5]. The experiments show for the first time that pulse trains from such sources can be transmitted with low distortion over terrestrial distances and can be controlled and detected electronically.

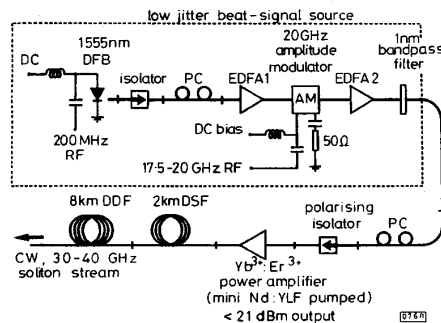


Fig. 1 Experimental setup

The source configuration (Fig. 1) consists of three principal components: an optical beat-signal source, an Er<sup>3+</sup>/Yb<sup>3+</sup> optical power amplifier and a dispersion-varying fibre section. To obtain a low timing jitter beat signal, the output of a CW DFB laser was externally modulated using a 20GHz amplitude modulator tuned