An Optical CDMA System Based on Spectral Encoding of LED

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***Abstract*—In this letter we propose an optical code-division multiple access (CDMA) system based on amplitude spectral encoding of low-cost broadband sources such as light-emitting-diodes. The proposed system uses a standard nondispersive lens-grating apparatus, and simple direct-detection receivers. We show that by assigning to N subscribers the N cycles shifts of a single unipolar m-sequence of period N, complete orthogonality between the users can be achieved, provided that the spectrum is properly equalized. We show that without any equalization, and for $N = 511$, up to 200 users can transmit asynchronously with an average error probability equal to 10^{-9}, depending on the received power level. An aggregate network throughput of 100 Gb / s can therefore be obtained.**

I. INTRODUCTION

OPTICAL code-division multiple access (CDMA) networks based on frequency-domain encoding of coherent [1] and noncoherent [2] broad-band sources have been proposed recently. In the former case, high-cost mode-locked lasers providing ultrashort pulses are necessary, as well as complicated receivers including optical threshold elements and optical correlators. In the latter case, encoding/decoding is done with guided-wave ladder networks, and to achieve coherence correlation, the delays at the receiver need to match those at the transmitter to within the coherence time of the noncoherent source. This is typically less than 1 ps and therefore requires complex electronics, such as feedback control loops in order to compensate the change in optical path lengths induced by temperature variations [2].

In this letter we propose an optical CDMA system based on amplitude spectral encoding of low-cost broadband sources such as LED's. Our system requires only standard optical elements and simple direct-detection receivers. We show that tens to hundreds of users can transmit asynchronously with negligible probability of error, giving an aggregate network throughput in the range of 50–100 Gb/s. Furthermore, since the spectral width of an LED is independent of the modulating signal, the so-called spreading gain is independent of the data rate, a major advantage in CDMA systems.

II. PRINCIPLE OF OPERATION

Fig. 1 shows a schematic diagram of the proposed system. We assume a passive star coupler is used to connect the local network users although any configuration is acceptable. Since the codes used by the users dictate the receiver design, we first describe them. We propose using simple unipolar m-sequences to encode the spectrum of LED's. The unipolar sequence $(\boldsymbol{x}) = (x_0, x_1, x_2, \cdots, x_{N-1})$ of period N is obtained from the bipolar version by replacing each binary 1 by a 0 and each -1 by a 1. The autocorrelation is then

$$\Theta_x(k) = \sum_{i=0}^{N-1} x_i x_{i+k} \tag{1}$$

which results in $\theta_x(0) = (N+1)/2$ for $k = 0$ and to $\theta_x(k) = (N+1)/4$ for $k = 1$ to $N-1$. The sum $i + k$ is taken modulo N. These results come from the shift-and-add property of m-sequences [3] which says that the modulo-2 sum of an m-sequence and any cycle phase shift of the same m-sequence is another phase of the same sequence. In other words, half of the 1's in $(\boldsymbol{x})^k$ coincide with the 1's of $(\boldsymbol{x})$ while the other half coincide with the 0's, where $(\boldsymbol{x})^k$ is the k cycle shift of $(\boldsymbol{x})$. A receiver that computes:

$$\begin{aligned} Z &= \sum_{i=0}^{N-1} x_i x_{i+k} - \sum_{i=0}^{N-1} (1 - x_i) x_{i+k}, = 2\Theta_x(k) - \Theta_x(0) \\ &= 2 \times (N+1)/4 - (N+1)/2 = 0 \end{aligned} \tag{2}$$

will reject the signal coming from the interfering user having sequence $(\boldsymbol{x})^k$. This is true for any k, and by assigning the N cycle shifts of a single m-sequence to N subscribers, we have a network that can support N simultaneous users without any interference. Complete orthogonality between the users is theoretically achieved.

III. TRANSMITTER AND RECEIVER DESCRIPTION

Encoding of broad-band sources can be done in different ways, one being the well-known [4] temporally nondispersive lens and grating apparatus shown in Fig. 1. After direct intensity modulation of the LED according to the data (we assume ASK modulation), the signal is reflected from the grating where the different wavelengths are angularly dispersed and focused by the lens on the plane of the spatially patterned amplitude mask. A second lens and grating recombine the unfiltered spectral components into a single optical beam which is then sent to all receivers via a passive star coupler.

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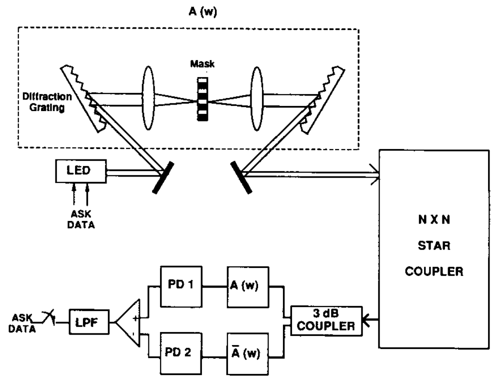

Fig. 1. Schematic diagram of the proposed optical CDMA system.

The number of nonoverlapping "slices" that can be performed in the spectrum of LED by the amplitude mask dictates the length of the m-sequence and therefore the number of subscribers. The number of distinct spectral features that can be achieved is approximately given by $N = 0.5 \times (\delta\lambda/\lambda) \times (\pi w/d \cos\theta_r)$ [5] where λ is the center wavelength of the source, $\delta\lambda$ is the spectral width being encoded, w is the input beam radius, d is the grating period and θ_r is the diffracted angle of the center wavelength. For $\delta\lambda = 50$ nm (typical FWHM for a LED), $\lambda = 1.5$ μm, $w = 2$ mm, $1/d = 1200$ lines/mm grating and $\theta_r = 68°$ (for Littrow configuration), we compute $N =$ 325 users. With a 1800 lines/mm grating and an input beam radius $w = 1.5$ mm we can accommodate $N = 730$ users.

It is interesting to compare this capacity with a WDM multi/demultiplexer based on grating devices and using LED's, such as the spectrally sliced WDM systems [6]. In these cases, a resolution limit of about 1 nm/user is achieved (50 users for 50 nm LED) due to the need to couple each slice of the spectrum into different optical fibers, which is not the case here. Furthermore, in our proposed system each user is allowed to use one half of its LED power since the ratio of 1's in a m-sequence is $(N + 1)/(2N) \approx 0.5$. In a spectrally sliced WDM system each user is restricted to $1/N$ of its LED power, N being the number of subscribers.

The receiver needs to compute Z in (2). This is done by using two photodetectors, one to receive $\Sigma x_i x_{i+k}$ and the other to receive $\Sigma(1 - x_i)x_{i+k}$ and subtracting their outputs. One easy way of doing this, although probably not the most efficient, is to split the incoming signal in two parts, each one going through a separate lens and grating apparatus. Two masks that transmit complementary frequency bands are needed. The notation $\bar{A}(w)$ in Fig. 1 simply means that the mask pattern in that branch is the opposite of the one used for $A(w)$. Another way which uses only one encoding apparatus, is to replace the spherical lenses by cylindrical lenses and to use a two-dimensional mask, where one dimension is still used for the frequency while the other is used to place the two complementary amplitude patterns. Note that, the desired signal is received only by photodetector 1, so that a 3 dB loss due to the coupler is inherent to the detector. Note also that, at the receiver, the second grating usually used to combine the different unfiltered wavelengths is not needed since they can be focused directly onto the photodetector.

In the above discussion it was implicitly assumed that all the 1's in the sequence will appear as 1's at the photodetector. However, the spectrum of an LED is not flat but might exhibit for example a gaussian shape, meaning that some 1's will be seen as different values depending on the position they take along the spectrum. The consequence of that will be a loss of perfect orthogonality between the users. There are basically three ways to counter this effect. The first is to use programmable spatial light modulators (SLM), such as liquid crystal devices, in order to obtain nonbinary amplitude transmissions. Alternatively, one can assign different lengths of frequency bands depending on the chips positions in the codes, so that the power transmitted in each band will be the same. This, however, increases the complexity of mask fabrication. The second one is to equalize the LED spectrum by using acousto-optic tunable filters, in the same way they have been used in optical systems with optical amplifiers [7]. Finally, one can simply reduce the length of total frequency band that is encoded to be in the center of spectrum which is more flat. In the next section we concentrate on this solution and calculate the average probability of error so obtained. A Gaussian shape is assumed for the LED spectrum.

IV. PERFORMANCE CALCULATION

Assuming the lowpass filter is a simple integrate-and-dump receiver, we write:

$$z(T) = \int_0^T (y_1(t) - y_2(t))\, dt \tag{3}$$

where $z(T)$ is the decision variable at time T resulting from the integration of the difference of the two photodetectors outputs $y_1(t)$ and $y_2(t)$. Using Gaussian statistics for $z(T)$, but taking into account the shot noise nature of the two independent processes $y_1(t)$ and $y_2(t)$ we only need to calculate the mean and variance of $z(T)$. If the variable P is the power that would be received from one interfering user if no spectral filtering was done at the transmitter or receiver, the result is

$$\eta_z = \gamma a T + \frac{T\gamma}{2} \sum_{k=1}^{K} (b_k - c_k) \tag{4}$$

$$\sigma_z^2 = \gamma a T + \frac{T\gamma}{2} \sum_{k=1}^{K} (b_k + c_k) + \frac{T^2\gamma}{6} \sum_{k=1}^{K} (b_k - c_k)^2 \tag{5}$$

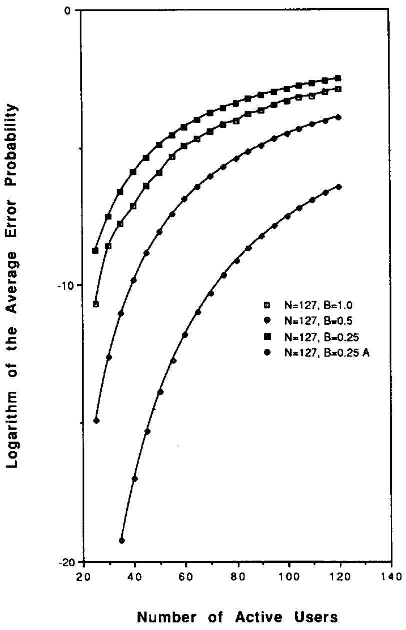

Fig. 2. Probability of error versus the number of active users for code length $N = 127$.

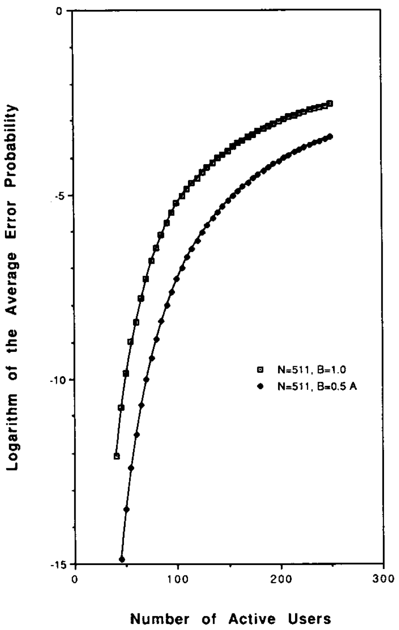

Fig. 3. Probability of error versus the number of active users for code length $N = 511$.

where

$$\gamma = \frac{RPBw}{(2\pi\sigma^2)^{1/2}}, \qquad a = \sum_{i=0}^{N-1} x_i \alpha_i$$

$$b_k = \sum_{i=0}^{N-1} (1 - x_i) x_{i+k} \alpha_i, \qquad c_k = \sum_{i=0}^{N-1} x_{i+k} \alpha_i$$

$$\alpha_i = \int_{(-1/2+i/N)\times B}^{(-1/2+(i+1)/N)\times B} e^{-2.77y^2}\, dy.$$

T is the bit period, R is the responsivity (A/W), Bw is the 3 dB bandwidth of the LED, (so $\gamma = 0.939\ P$) and B is the ratio of the frequency bandwidth encoded over the 3 dB bandwidth ($0 \leq B \leq 1$). Finally K is the number of interfering users ($1 \leq K \leq N - 1$). For our calculations we choose $1/T = 500$ Mb/s, and P so that a, the mean number of photoelectrons/bit from the desired user is ≈ 6000 (after spectral filtering we get -34 dBm). For that receiver sensitivity and at a bit rate of 500 Mb/s, we can neglect the thermal noise. If this is not the case, one would have to increase the transmitted power so that the system is not thermal-noise limited. In any case, our goal is to find the number of active users that can be supported when all subscribers use the same power and as such, will not be affected by the thermal noise level. Figs. 2 and 3 give the probability of error as a function of K for an m-sequence of period $N = 127$ and $N = 511$, respectively. It can be seen that reducing B from 1.0 to 0.5 decreases the average error probability since we are working in a part of the spectrum which is more flat. Reducing B further to 0.25, however, results in a higher average error rate. This is due to the shot noise, since reducing the encoded bandwidth also reduces the total received power. For $B = 0.25$ the power received is so small that the shot noise dominates. The curve labeled $N = 127$, $B = 0.25\ A$ is obtained by assuming that the power is increased so that the same amount is received with $B = 0.25$ and $B = 1.0$. The improvement is obvious. We see that 100 users can transmit with $N = 511$ without any equalization of the LED spectrum. All these curves are very sensitive to the received power level. For example, increasing the received power to 1 uw allows 200 users at $Pe = 10^{-9}$ instead of 100. Note that, keeping the same N value while reducing B necessitates higher resolution masks. We mention that the probability of error will vary greatly from one receiver to another depending on which cycle of the m-sequence it has been given. This is due to the different distributions of 1's and 0's across the spectrum. We have plotted here only the worst case receiver. Finally, we mention that even though we are proposing an LED as the source, the power issue should not be a major problem since superluminescent diodes (SLD) with average output power of ≈ -5 dBm at 1480 nm (FWHM ≈ 70 nm) have been reported. Edge-emitting LED launching ≈ -6 dBm in single-mode fibers are also commercially available. Optical amplifiers could also be used at the expense of increased system cost and spectrum nonuniformity.

V. CONCLUSION

We have proposed a new Optical CDMA System based on amplitude spectral-encoding of LED's. By using a single m-sequence of period N, we have shown that N

subscribers can be accommodated by assigning a different cycle shift to each of them. Complete orthogonal transmissions is possible by using special designed masks or by equalizing the source spectrum. Without equalization, we have shown that for $N = 511$, the system can support 200 users with a $Pe = 10^{-9}$, giving a network throughput of 100 Gb/s.

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Nonregenerative Photonic Dual Bus with Optical Amplifiers

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***Abstract*—Nonregenerative photonic dual buses with passive optical access and optical amplification are investigated for transmission performance and potential network span. A novel two-wavelength system is proposed to improve the network capability, with one wavelength transmitted by the head of bus for distributing the clock and regulating the amplified spontaneous emission. The second wavelength is used by all nodes for network operations. It is shown that a multigigabit photonic dual bus with 100 nodes spanning hundreds of kilometers is possible. Major advantages of such networks are improved flexibility, reliability, uninterruptive maintenance, and graceful upgrade.**

INTRODUCTION

As high-speed local area networks, computers, and multimedia communications become increasingly pervasive, high-performance metropolitan-area and wide-area networks (MAN/WAN) are in great demand. It is important that service flexibility, network reliability, maintenance, and future upgrade are considered for such networks. In conventional lightwave networks, optical signals are terminated and regenerated at each node to prevent accumulation of noise, distortion, and loss. Such designs, however, are inflexible because only services of a fixed data rate are provisioned, and unreliable because a single component failure on the main line could paralyze the entire network. Today's lightwave transmission technology has been dramatically improved by optical amplifiers. Transmission of multigigabit data over thousands of km with only minor penalties is achieved [1], [2]. Since photonic networks without electronic regeneration are like transparent light pipes with only passive components on the main line, they are potentially advantageous in flexibility, reliability, and graceful upgrade. This letter investigates and proposes a photonic dual bus (PDB) with optical amplification as a subnetwork of MAN/WAN. Transmission performance analysis and potential network span for 10 Gb/s PDB are presented.

NETWORK CONFIGURATION

A nonregenerative PDB with N nodes in a looped configuration is shown in Fig. 1(a), with the node interface designs depicted in Fig. 1(b) and 1(c) for the head and intermediate nodes, respectively. Two optical carriers ($\lambda 1$, $\lambda 2$) with separate wavelength are used in a narrow optical band ($\sim$ 2–3 nm) where fiber dispersion effect can be minimized. Carrier $\lambda 1$ is continuously transmitted from the head of bus (node 1), carrying the system clock on a pilot tone for network synchronization. As will be shown, $\lambda 1$ also serves to regulate the amplified spontaneous emission (ASE) power which will otherwise severely restrict the size of the network. $\lambda 2$ is used by all nodes for distributed queue dual bus (DQDB) [3], or similar network operations. The system clock is directly distributed because the conventional method of extracting the clock from the data burst will be inefficient in high-speed photonic networks. For buses with large span, the phase

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