Design and analysis of a dynamic spectral encoding code-division multiple-access communication system

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Abstract. An optical dynamic spectral encoding code division multiple access (CDMA) communication system is proposed. In this system, an electrically controlled tunable optical filter (TOF) is used to encode the modulated broadband light source. The code depends on the function set to the controller. Two-dimensional code, named functional code, is also proposed based on a shifted sine function. The function defines the dynamic coding pattern of the central wavelength of the transmitted narrowband optical signal. Thus, the system will allow for an easy reconfiguration of the transmitter without the need for a sophisticated encoder. At the receiver, a synchronized TOF with the same function is used as a decoder. The system is modeled and analyzed taking into account the multiple access interference, phase-induced intensity noise (PIIN), and thermal noise. The performance of this system is shown to be better compared with a fast frequency hopping (FFH) system and a spectral amplitude coding (SAC) system that uses either a Hadamard code, a modified quadratic congruence (MQC) code, or a modified frequency hopping (MFH) code. [DOI: 10.1117/1.2359455]

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1 Introduction

Many optical CDMA communication schemes have been proposed in the last two decades. The most attractive incoherent schemes are direct sequence (DS), spectral amplitude coding (SAC), and fast frequency hopping (FFH) optical CDMA systems. A DS optical CDMA system encodes the incoherent pulses in the time domain and recovers the data at the receiver using taped delay lines. The performance of this system is poor because of the correlation properties of the unipolar codes used, which contribute to a high level of multiple access interference (MAI).[1] The SAC scheme is a more recent technique in optical CDMA systems where the spectrum of a broadband source is amplitude-encoded. In these systems, MAI can be canceled by using balanced detection and the code sequences with fixed in-phase cross correlation.[2] However, its performance is still limited by phase-induced intensity noise (PIIN).[3,4] The FFH system was proposed in the late 1990s, and it utilizes both time and frequency domains for encoding the optical signal.[5] Frequency separation between successive chip pulses is required in the FFH-CDMA system to reduce the side lobe effects of the gratings. This limits the maximum number of users in the system. Furthermore, the spatial distance between the gratings and the number of gratings limits the users' data rate in the system. Moreover, all of the preceding systems are either nonreconfigurable or need complicated reconfigurable encoders.[1,5,6]

In this paper, we propose an easily reconfigurable dynamic spectral encoding optical CDMA (DSE-OCDMA) system. The encoder varies the central frequency of a pulse of optical signal according to the functional code set to the controller. The system can recover the encoded data by matched decoders at the receiver. In DSE-OCDMA, the tunable optical filter (TOF) should be able to follow the functional code given as an electrical signal by the controller during one bit interval. The small data bit interval of the high data bit rate system requires fast TOF or special code with a tuning range suitable to the speed of the TOF. However, tunable optical filters that can scan tens of nm within a few ns have been reported.[7] Thus, the encoder and decoder can be easily and quickly reconfigured to any of the functional codes. The implementation of the system will be shown to lead to better performance of the network. It is shown here that the system's performance is better than that of the SAC and FFH systems recently proposed.[3–5]

2 System Configuration and Description

The block diagram in Fig. 1(a) shows the DSE-OCDMA configuration. The broadband signal from the light source is on-off key (OOK)-modulated with the binary data. If the data bit is 1, the encoder $j, j \in \{1, 2, \ldots, K\}$, where K is the number of simultaneous users, filters the spectrum of the pulse at a central wavelength varying with time according to a functional code $F^j(t)$; otherwise, no power is transmitted. The encoder is a tunable optical filter controlled with an electrical signal that represents the functional code. Part

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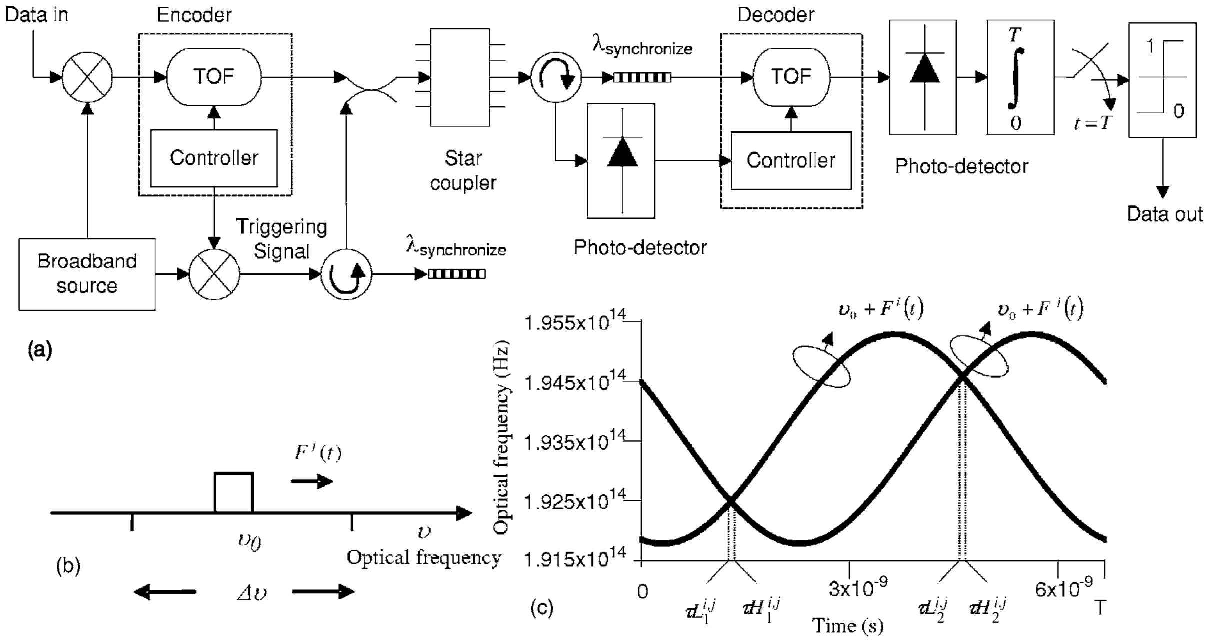

Fig. 1 (a) Block diagram of dynamic spectral encoding OCDMA system. (b) Optical spectrum of a signal from one of the users. (c) Power spectral density for two users as a function of time and frequency.

of the bandwidth ($\lambda_{synchronize}$) is reserved for synchronization between the transmitter and receiver TOFs. The controller sends a triggering signal to a modulator to produce a broadband triggering signal. A small bandwidth triggering signal is reflected from the fiber Bragg grating (FBG) filter and combined with the data signal using a 2:2 coupler. Signals transmitted from all synchronized users will be combined using a star coupler before they are received by all users. Synchronizing optical CDMA system relaxes some of the features of CDMA to gain other advantages. It has advantages over asynchronous CDMA in terms of an increased number of users.[8–10] At the receiver, the composite signal is decoded by a matched TOF. Another FBG filter at the decoder is used to recover the triggering signal which will be used by the controller to recover the data encoded in the broadband optical signal. The signal then passes through a photodetector, an integrator, and a threshold decision circuit to recover the transmitted data.

The source spectra are assumed to be flat over the bandwidth of $\upsilon_0 \pm \Delta\upsilon/2$, with magnitude $P_r/\Delta\upsilon$, where υ_0 is the central optical frequency, $\Delta\upsilon$ is the system bandwidth, and P_r is the received effective average power from a single source. Any excess losses in the route of the signal and the receiver are assumed to be incorporated in P_r. Ideal masking at the TOF is also assumed, and each user is considered to have the same effective average power at each receiver.

Figure 1(b) shows the spectrum of the j'th user's transmitted signal when the data bit is 1. It is similar to the spectrum of an ideal filter with central frequency varying with time according to a functional code. The proposed functional codes family $F(t)$ is a shifted sine functions family with the same frequency and different phase shifts. Figure 1(c) shows an example of the spectrum for two users at the input of the decoder during one bit period when both users are sending a bit of 1. At the receiver side, the TOFs of the decoders are synchronized in time with a phase shift related to the functional code for each of them. The output of the decoder is therefore the original signal, which has the same phase shift as the decoder with some interference at the points of intersection with other users.

3 Code Construction

The main criterion in the functional codes construction is to minimize the number of intersecting points between any pair of functions because they increase the interfering power between users. The area of intersection between any two functions is related directly to the value of interfering power and it is also important parameter in the construction of the functional codes. In our proposal, we have considered the use of shifted sine code (SSC) functions to alter the optical central frequency (υ_0) and to code the transmitted signal. The code family is given by:

$$F^j(t) = \frac{\Delta\upsilon}{2}\sin(2\pi f t - j\varphi), \tag{1}$$

where f is the frequency of the functional code, and φ is the phase shift between different functions. Shifted sine functions are proposed for their simplicity and the possibility of achieving the large number of required codes by reducing the phase shift.

The TOF in DSE-OCDMA should be able to follow the functional code driving the filter. The required speed of the TOF and its controller is defined as the derivative of the code and is given by:

$$S^j(t) = \Delta\upsilon\pi f\cos(2\pi f t - j\varphi). \tag{2}$$

It is directly proportional to the frequency and amplitude of the functional code. The example shown in Fig. 1(c) also represents the codes of two users at a data bit rate of 155 Mbps and a system working at 1550 nm with a bandwidth of 30 nm. Thus, the speed of the TOFs required for this system is a sinusoidal value varying from 0 to 14.6 nm/ns. Other codes could be proposed to improve the system performance and relax the implementation of the system for high data bit rates.

Furthermore, the functional codes should start and stop at the same central wavelength during the data bit interval (T) for smooth modulation of the TOF and its controller. This also limits the frequency of the code to be an integer value of $(1/T)$. For these reasons, we use the smallest frequency possible for the SSC that equals the data bit rate. Phase shift between codes (φ) is related to the spacing between users and the code size. A smaller phase shift results in a larger family of codes, but it reduces the spacing between users in the spectrum. The phase shift of SSC functions is chosen to be $2\pi/169$, which results in 170 different codes and is the same as the cardinality of the modified quadratic congruence (MQC) family of codes with $p=13$.[2]

4 DSE-OCDMA Performance Analysis

In the analysis of the bit error rate (BER), we consider the effect of the MAI, the PIIN, and the thermal noise. Other sources, like shot noise and receiver's dark current noise are neglected. Gaussian approximation is assumed for the distribution of the noise in the calculation of the BER.

The variance of a photocurrent detected from an unpolarized thermal light source generated by spontaneous emission, including the effect of MAI, can be expressed as:

$$\sigma_t^2 = (K-1)\sigma_{DAI}^2 + I^2 B\tau_c + 4K_b T_n B/R_L, \tag{3}$$

where $(K-1)\sigma_{DAI}^2$ is the variance of the MAI, σ_{DAI}^2 is the variance of the interference when two users access the network, I is the average photocurrent, B is the noise-equivalent electrical bandwidth of the receiver, τ_c is the coherence time, K_b is the Boltzmann constant, T_n is the absolute receiver noise temperature in Kelvin, and R_L is the receiver load resistor. The first term of this equation represent the MAI effect. The second term denotes the effect of PIIN, where incoherent light sources are mixed at the input of the photodetector and cause intensity variations of the output current. Finally, the third term represents the effect of thermal noise.

The power spectral density $G(\upsilon,t)$ of the signal at the input of the receiver $m, m\in\{1,2,\ldots,K\}$, is the sum of all active users' transmitted signals:

$$G_m^e(\upsilon,t) = \frac{P_r}{\Delta\upsilon}\sum_{j=1}^{K} b^j rect\left[\frac{\upsilon-\upsilon_0-F^j(t)}{BW}\right], \tag{4}$$

where $rect(\upsilon-\upsilon_0/BW)=u(\upsilon-\upsilon_0+BW/2)-u(\upsilon-\upsilon_0-BW/2)$, $u(\upsilon)$ is the unit step function, BW is the bandwidth of the TOFs, and b^j is the data bit value of user j.

The receiver applies a synchronized matched TOF in decoding the incoming signal to extract the desired users data bit stream. The decoder output is:

$$\begin{aligned} G_m^d(\upsilon,t) = {} & \frac{P_r}{\Delta\upsilon} b^m rect\left[\frac{\upsilon-\upsilon_0-F^m(t)}{BW}\right] \\ & + \left\{\frac{P_r}{\Delta\upsilon}\sum_{j=1,j\neq m}^{K} b^j rect\left[\frac{\upsilon-\upsilon_0-F^j(t)}{BW}\right]\right\} \\ & \times rect\left[\frac{\upsilon-\upsilon_0-F^m(t)}{BW}\right]. \end{aligned} \tag{5}$$

The photocurrent is:

$$\begin{aligned} I_m(t) = {} & \Re\int_{\upsilon=0}^{\infty} G_m(\upsilon,t)\ \mathrm{d}\upsilon = \Re\frac{P_r}{\Delta\upsilon} b^m BW \\ & + \Re\frac{P_r}{\Delta\upsilon}\sum_{j=1,j\neq m}^{K} b^j \sum_{i=1}^{N_{m,j}} [BW - |F^m(t)-F^j(t)|] \\ & \times[u(t-\tau L_i^{m,j}) - u(t-\tau H_i^{m,j})], \end{aligned} \tag{6}$$

where $\Re=(\eta e)/(h\upsilon_0)$ is the responsivity of the photodetector, η is the quantum efficiency, e is the electron's charge, h is Planck's constant, $N_{m,j}$ is the number of intersecting points between users m and j during one bit period, and $\tau L_i^{m,j}$ and $\tau H_i^{m,j}$ are defined as the roots of the following equations, respectively [see Fig. 1(c)]:

$$F^m(t) - F^j(t) - BW = 0, \tag{7}$$

$$F^m(t) - F^j(t) + BW = 0. \tag{8}$$

After the integrator and sampler, the optical photocurrent is:

$$\begin{aligned} I_m = {} & \frac{1}{T}\int_{t=0}^{T} I_m(t)\ \mathrm{d}t = \Re b^m \frac{P_r}{\Delta\upsilon} BW \\ & + \Re\frac{P_r}{T\Delta\upsilon}\sum_{j=1,j\neq m}^{K} b^j \sum_{i=1}^{N_{m,j}} [BW(\tau H_i^{m,j} - \tau L_i^{m,j}) \\ & - \int_{L_i^{m,j}}^{\tau H_i^{m,j}} |F^j(t) - F^m(t)|/dt]. \end{aligned} \tag{9}$$

The optical photocurrent at the receiver of user m, $m\in\{1,2,\ldots K\}$, after the integrator and sampler can be reformulated as:

$$I_m = b^m I + MAI(m), \tag{10}$$

where $I=\Re P_r BW/\Delta\upsilon$, and the multiple access interference at receiver m, $MAI(m)$ is given by:

$$MAI(m) = \sum_{j=0,j\neq m}^{K} DAI(m,j), \tag{11}$$

where:

$$DAI(m,j) = \Re \frac{P_r}{T\Delta\upsilon} \sum_{i=1}^{N_{m,j}} \left[BW(\tau H_i^{m,j} - \tau L^{m,j}{}_i) - \int_{\tau L_i^{m,j}}^{\tau H_i^{m,j}} \left| F^j(t) - F^m(t) \right| \, \mathrm{d}t \right], \tag{12}$$

is the interference between users m and j.

In Eq. (10), the first term is the data bit of the desired user m, and the second term is the MAI noise. Since our system is synchronized, users m and j will interfere at the same points in time relative to the beginning of the bit period, and the intersecting edges $\tau L^{m,j}{}_i$ and $\tau H^{m,j}{}_i$ are the same whenever users m and j are active. This results in a constant value of $DAI(m,j)$ if users m and j are active; otherwise, $DAI(m,j)$ is zero. $DAI(m,j)$ is a random variable with average and variance given in Eqs. (13) and (14), respectively:

$$\mu_{DAI} = \frac{1}{K^2 - K} \sum_{m=1}^{K} \sum_{j=1, j\neq m}^{K} DAI(m,j), \tag{13}$$

$$\sigma_{DAI}^2 = \frac{1}{K^2 - K} \sum_{m=1}^{K} \sum_{j=1, j\neq m}^{K} [DAI(m,j) - \mu_{DAI}]^2. \tag{14}$$

Because the interference values from different users are independent, we can use the central limit theorem to find the variance of MAI as $(k-1)\sigma_{DAI}^2$ for k simultaneous active users.

The PIIN causes variations in the output current during interference of incoherent light sources at the input of the photodetector. The variance of the PIIN is related to the coherence time of the source (τ_c), as shown in Eq. (3), which is given by:

$$\tau_c(t) = \int_{\upsilon=0}^{\infty} G_m^2(\upsilon,t) \, \mathrm{d}\upsilon \Big/ \int_{\upsilon=0}^{\infty} G_m(\upsilon,t) \, \mathrm{d}\upsilon^2. \tag{15}$$

Assuming no more than one pair of users interfering at a time, which is the case in our proposed functional code family, averaging the variance at the points of interference along the bit period and averaging over all users, the PIIN variance equation can be given by:

$$\overline{\sigma_{PIIN}^2} = \frac{1}{K} \sum_{m=1}^{K} \frac{1}{T} \int_0^T B\Re^2 \sum_{j=1, j\neq m}^{K} \sum_{i=1}^{N_{m,j}} \left\{ \left(\frac{P_r}{\Delta\upsilon} b_m + \frac{P_r}{\Delta\upsilon} b_j \right)^2 [BW - |F^m(t) - F^j(t)|] + \left(\frac{P_r}{\Delta\upsilon} b \right)^2 |F^m(t) - F^j(t)| \right\} \times [u(t - \tau L_i^{m,j}) - u(t - \tau H_i^{m,j})] \, \mathrm{d}t. \tag{16}$$

The variance of the PIIN for k users can be expressed as $\sigma_{PIIN}^2 = k\overline{\sigma_{PIIN}^2}$. From (3), (14), and (16), the signal-to-noise ratio can be expressed as:

$$SNR(k) = I^2 / [(k-1)\sigma_{DAI}^2 + \sigma_{PIIN}^2 + 4K_b T_n B / R_l], \tag{17}$$

and using Gaussian approximation, the BER is given by:

$$BER(k) = (1/2)\mathrm{erfc}\{[SNR(k)/2]^{1/2}\}. \tag{18}$$

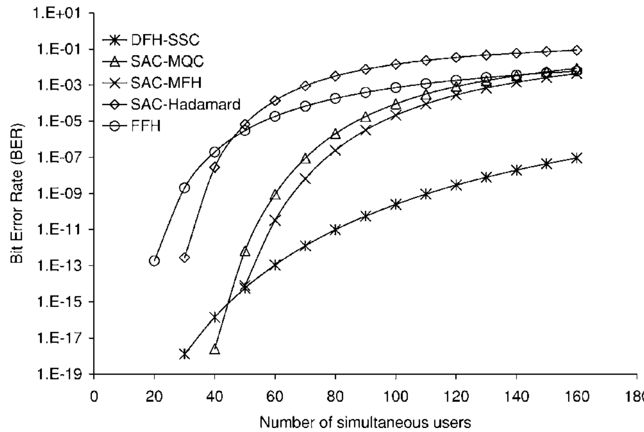

Fig. 2 Probability of error comparison between different optical CDMA systems.

5 Results and Discussion

The BER for the DSE-OCDMA using the proposed sine functional code family and another two OCDMA systems—one FFH and the other SAC using either Hadamard code, MQC code[2] with $p=13$, or modified frequency hopping (MFH) code[3] with $q=16$—are plotted in Fig. 2 for the sake of comparison. Figure 2 shows the relation between the BER and the number of simultaneous active users when $P_r = -10$ dBm.

In our calculations, we take $\Delta\upsilon = 30$ nm, $\upsilon_0 = 1550$ nm, $BR = 155$ Mbps, and filter bandwidth $BW = 0.165$ nm which is equal to the chip width of the SAC system using MQC with $p=13$ and the same optical bandwidth.

For an error rate of 10^{-11}, the DSE-OCDMA can accommodate up to 80 users, whereas for other systems, the maximum simultaneous users are 32 for the SAC system using Hadamard code, 52 for the SAC system using MQC code, 58 for the SAC system using MFH code, and 24 for the FFH system. The BER of the DSE-OCDMA system increases at a slower rate than that of the other two systems, which indicates that there is a significant improvement in performance with a large number of users. Indeed, it is shown that the BER for the DSE-OCDMA is better than any other system with any number of users more than 50. However, for fewer than 50 active users, the SAC system with MFH or MQC gives a BER better than that of the DSE-OCDMA system. It should be noted that for this range of users, the error rate is too small (less than 10^{-14}).

6 Conclusion

We have proposed a low-noise DSE-OCDMA communication system using a two-dimensional functional code. The encoder/decoder design is based on a fast, tunable optical filter. The filters is controlled dynamically and moves one cycle during the data bit period. This encoder is easily reconfigured to any code by changing the electrical signal of the controller. The system is analyzed with a simple shifted sine functional code family, taking into account the MAI, the thermal noise, and the PIIN. The system shows a very small BER with a large number of simultaneous active users compared with other systems such as SAC and FFH OCDMA systems. At 100 users, for example, the system

BER is only 10^{-10}, while for all other systems, it is greater than 10^{-5}. In the proposed system, the data transmission rate is limited by the tunable filter's tuning speed, but other functional code families can be used to reduce the requirement for tuning speed so that the system can support higher bit rates.

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