CONFIGURATION DESIGN AND PERFORMANCE ANALYSIS OF A FAST FREQUENCY MODULATION OPTICAL CDMA COMMUNICATION SYSTEM

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ABSTRACT

A fast frequency modulation optical 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 functional code is also proposed based of shifted sine function. The function defines the dynamic coding pattern of the central wavelength of the transmitted narrowband optical signal. The system allows for an easy reconfiguration of the transmitter without the need for sophisticated encoder. At the receiver, a synchronized TOF with the same function is used as a decoder. The performance of this system is shown to be better compared with a fast frequency hopping and a spectral amplitude coding systems.

***Keywords:* Multiple access interference, optical code division multiple access (CDMA), optical fiber communication.**

1.0 INTRODUCTION

Many optical CDMA communication schemes have been proposed in the last two decades. Attractive incoherent schemes are, among others, direct sequence (DS), spectral amplitude coding (SAC), and fast frequency hopping (FFH) optical CDMA systems. DS optical CDMA system encodes the incoherent pulses in 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 contributes to a high level of multiple access interference (MAI) [1]. SAC scheme is a more recent technique in optical CDMA systems where the spectrum of a broadband source is amplitude-encoded. In both systems, MAI can be canceled by balanced detection and code sequences with fixed in-phase cross correlation [2]. However, its performance is still limited by phase induced intensity noise (PIIN) [3][4]. FFH system was proposed in the late 1990's and it utilizes both time and frequency domains for encoding the optical signal [5], [6]. Frequency separation between successive chip pulses is required in 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 bit rate in the system. Moreover, all the above systems are either non-reconfigurable, or they need complicated reconfigurable encoders [1], [5], [7].

In this paper we propose an easily reconfigurable fast frequency modulation optical CDMA (FFM-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 FFM-OCDMA, the 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 tuning range suitable with the speed of the TOF. However, tunable optical filters which can scan 10's of nano-meters within few nanoseconds have been reported [8], [9]. Thus, the encoder and decoder can be easily and quickly reconfigured to any of the functional codes. The implementation of the system leads to better performance of the network. It is shown here that the system performance is better than that of SAC and FFH systems recently proposed [3], [4], [5], [6].

2.0 SYSTEM CONFIGURATION AND DESCRIPTION

The block diagram in Fig. 1(a) shows the FFM-OCDMA configuration. The broadband signal from the light source is modulated with the binary data using On-Off Keying technique. If the data bit is "1", encoder $j, j \in \{1,2,...,K\}$, where K is the number of simultaneous users, filters the spectrum of the pulse at a central wavelength varies with time according to a functional code $F^j(t)$, otherwise no power is transmitted. The encoder is a TOF controlled with an electrical signal that represents the functional code. Thus, the output from the TOF is a fixed power signal with a wavelength changing with time according to the function at the output of the controller. Signals transmitted from all synchronized users will be combined using a star coupler.

At the receiver, the combined signal from all users is decoded by a matched TOF. The central wavelength of the filter varies with time according to the functional code of the receiver. Only the part of the composite signal, encoded with the same functional code of the receiver, passes through and all other signals are rejected. In addition, some interference power passes through at the intersecting points between the receiver functional code and other interfering codes. Then, the composite signal passes through a photo-detector, which converts it to electrical signal. The signal also passes through an integrator and a sampler to average the power during the data bit period, and a threshold decision to recover the transmitted data.

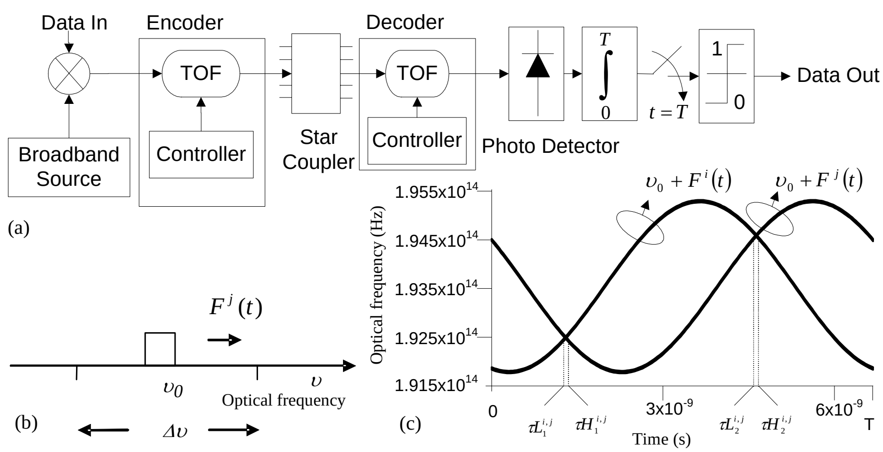

Fig. 1: (a) Block diagram of FFM-OCDMA system. (b) Optical spectrum of a signal from one of the users. (c) Power spectral density for two users as a function of time and frequency.

The broadband source spectra is 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 tunable optical filter is also assumed, and each user is considered to have the same effective average power at each receiver.

Fig. 1(b) shows the spectrum of j^{th} user's transmitted signal when the data bit is "1". The central wavelength of this signal changes with time during the data bit period. The central wavelength increases and decreases from the initial central wavelength value υ_0 according to the functional code. 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 shifted sine functions family with the same frequency and different phase shifts. Fig. 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". Thus, the power of the optical signal from each user, which is represented as black solid line, varies according to the shifted sine function of that user. At the receiver side, the TOFs of the decoders are synchronized in time with a phase shift related to the functional code for each one of them. In other words, the transmitters' central wavelength variation should be synchronized with that of the receiver. The output of the decoder, when both signals are synchronized is, therefore the original signal which has the same phase shift of the decoder with some interference at the points of intersection with other users $\tau_1^{m,j}, \tau_2^{m,j}$. Small portion of the bandwidth can be used to control the synchronization or any other method, however synchronous transmission implementation is not considered in this paper.

3.0 CODE CONSTRUCTION

The main criterion in the functional codes construction is to minimize the number of intersecting points between any pair of functions since 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 an 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,

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

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 FFM-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 given by,

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

The speed is directly proportional to the frequency and amplitude of the functional code. Thus, 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 which equals to the data bit rate. The phase shift between codes (φ) is related to the spacing between users and the code size. 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 $2\pi/169$, that results of 170 different codes which is the same as the cardinality of MQC family of codes with $p = 13$ [2].

4.0 FFM-OCDMA PERFORMANCE ANALYSIS

In the analysis of bit error rate (BER) we consider the effect of MAI, PIIN, and the thermal noise. Other sources, such as 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 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's 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 represents 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 receiver $m, m \in \{1,2,...K\}$ 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 $rect\left(\frac{\upsilon-\upsilon_0}{BW}\right) = u\left(\upsilon-\upsilon_0+\frac{BW}{2}\right) - u\left(\upsilon-\upsilon_0-\frac{BW}{2}\right)$, $u(\upsilon)$ is the unit step function, BW is the Bandwidth of the TOF's, 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,

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

Then, the photocurrent is,

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

where $\Re = (\eta e)/(h\upsilon_0)$ is the responsivity of the photo-detector. Here η is 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 $\tau L_i^{m,j}, \tau H_i^{m,j}$ 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 photo-current is,

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

The optical photo-current at the receiver of user m $m \in \{1,2,...K\}$ 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,

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

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 $\tau L_i^{m,j}$ and $\tau H_i^{m,j}$ 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 Eq.s (13) and (14) respectively,

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

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

The variance of MAI can be approximated 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 photo-detector. 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,

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

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,

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

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

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

and using Gaussian approximation, the BER is given by,

$$BER(k) = (1/2)\, erfc\left(\sqrt{SNR(k)/2}\right) \tag{18}$$

5.0 RESULTS AND DISCUSSION

The BER for FFM-OCDMA using proposed sine functional code family, and another two OCDMA systems, FFH and SAC using either Hadamard code, MQC code with $p = 13$ [2], or MFH code with $q = 16$ [3], are plotted in Fig. 2 for the sake of comparison. It 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 SAC system using MQC with $p = 13$ and same optical bandwidth.

For an error bit rate of 10^{-11}, FFM-OCDMA can accommodate up to 80 users, whereas for other systems, the maximum simultaneous users are: 32 for SAC system using Hadamard code; 52 for SAC system using MQC code; 58 for SAC system using MFH code; and 24 for FFH system. The BER of the FFM-OCDMA system is increasing at a slower rate than that of the other two systems, which indicates that there is a significant improvement in performance at large number of users. This also indicates that the noise power from interfering users is reduced in our system. This is achieved because the codes of two users interfere only during very short time in our system; while in SAC system, the interference power is more because the time of interference is longer and it is for the whole period of the data bit.

Indeed it is shown that the BER for FFM-OCDMA is better that any other system at any number of users of more than 50. However for less than 50 active users, SAC system with MFH or MQC gives a better BER than that of FFM-OCDMA system. This is because, in FFM-OCDMA system, the phase shift between functional codes is related to the maximum number of users supported not only to the number of simultaneous users in the network. It should be noted that for this range of users, the error rate is too small (less than 10^{-14}).

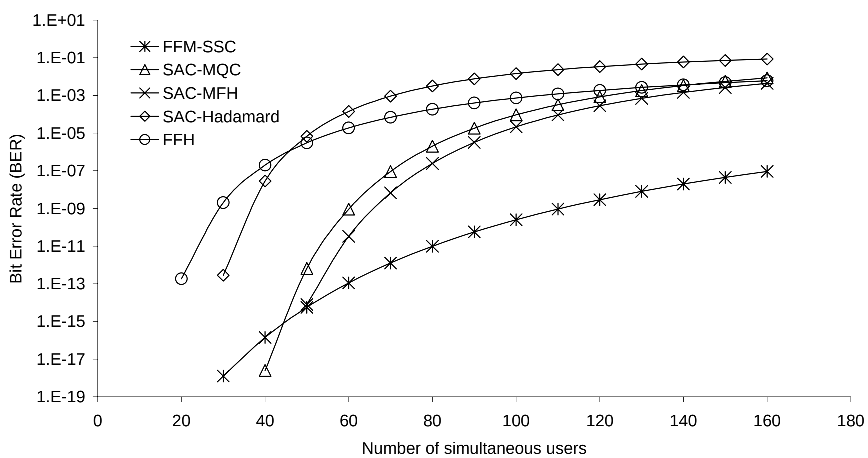

Fig. 2: Probability of error comparison between different optical CDMA systems.

6.0 CONCLUSION

We have proposed a novel low noise fast frequency modulation (FFM) OCDMA communication system using a novel two dimensional functional code. The encoder/decoder design is based on fast tunable optical filter. The filters are 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 sine shifted functional code family taking into account the multiple access interference, the thermal noise, and the phase induced intensity noise. The system shows very small BER at large number of simultaneous active users compared with other systems like spectral amplitude coding (SAC) and fast frequency hopping (FFH) OCDMA systems. At 100 users for example, the system BER is only 10^{-10}, while for the other two systems, the system BER is more than 10^{-5}. Although in the proposed system, the data transmission rate is limited by the tunable filter's tuning speed, other functional code families can be used whereby the requirement for tuning speed can be reduced so that the system can support higher bit rates.

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BIOGRAPHY

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