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# Novell Coding Technique for Code Division Multiple Access Communication system

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***Abstract*** – *An optical dynamic frequency hopping code division multiple access 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. The function defines the dynamic hopping 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 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, thermal noise, and phase induced intensity noise. The performance of this system is compared with a spectral amplitude coding system that uses either a Hadamard code or a modified quadratic congruence code.*

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

## I. INTRODUCTION

Early optical CDMA systems coded the incoherent pulses in time domain and recovered the data at the receiver using taped delay lines [1]-[3]. The performance of these systems is poor because of the correlation properties of the special unipolar codes used and the summation required [4],[5]. A more recent technique for optical CDMA is spectral amplitude coding (SAC) optical CDMA systems [6]-[11]. In these systems, the spectrum of broad-band sources is encoded. Further, the multiple access interference can be canceled in these systems by using code sequences with fixed in-phase cross correlation. The phase induced intensity noise (PIIN) is the main parameter that limits the performance of this type of systems [9].

In this letter we propose a dynamic optical CDMA (DOCDMA) system with signal clipping. The encoder modulates the central frequency of the pulse optical signal according to a functional code. The synchronized system can recover the encoded data by a matched tunable optical filter at the receiver. DOCDMA signals interfere only during the time of intersection between the functional codes driving the TOF's and this time limitation decreases the PIIN effect on the BER performance. It has been found that the PIIN is effectively suppressed using this system and the main noise source for this system is the multiple access interference (MAI). However, the system performance is still better compared to the SAC systems recently proposed [11].

This scheme uses codes based on wavelength modulation implemented with a single fast TOF in each encoder and decoder. This encoder and decoder configuration makes it easily reconfigured to any of the functional codes without the need for any hardware modification.

## II. SYSTEM CONFIGURATION AND DESCRIPTION

The block diagram in Fig. 1(a) shows the DOCDMA configuration. The broadband signal from the light source is OOK modulated with the binary data. For each data bit of "1", encoder $j, j \in \{1,2,\ldots,K\}$, where $K$ is the number of simultaneous users, will filter the spectrum of the pulse at a central wavelength which varies according to a functional code $F^j(t)$. The encoder is simply one fast tunable optical filter controlled with the functional code. Signals transmitted from all synchronized users will be mixed up in the network before received by all users. At the receiver, the composite signal is decoded by matched tunable optical filter. Then, the signal passes through a photodetector, an integrator, and a threshold decision to recover the data transmitted.

The source spectra are assumed to be flat over the bandwidth of $u_0 \pm \Delta u/2$, with magnitude of $P_r/\Delta u$, where $u_0$ is the central optical frequency, $\Delta u$ is the system bandwidth, and $P_r$ is the received power from a single user. 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. The transmitter sends a pulse with spectral distribution varying with time if the data bit value is "1"; otherwise no power is transmitted. Fig. 1(b) shows the spectrum of $j^{th}$ user's transmitted signal when the data bit is "1". The spectrum is similar to that of an ideal filter with central frequency varying with time according to a functional code. The proposed functional codes family $F(t)$ is 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". The TOFs of the decoders are synchronized in time with a phase shift related to the functional code for each one of them. The output of the decoder is therefore the signal which has the same phase shift with some interference noise at the points of intersection with other users.

## III. 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 which is related directly to the value of interfering power is also an important parameter in the construction of the functional codes. In our proposal, we suggest the use of shifted sine functions to alter the optical central frequency $(u_0)$ for coding the transmitted signal.

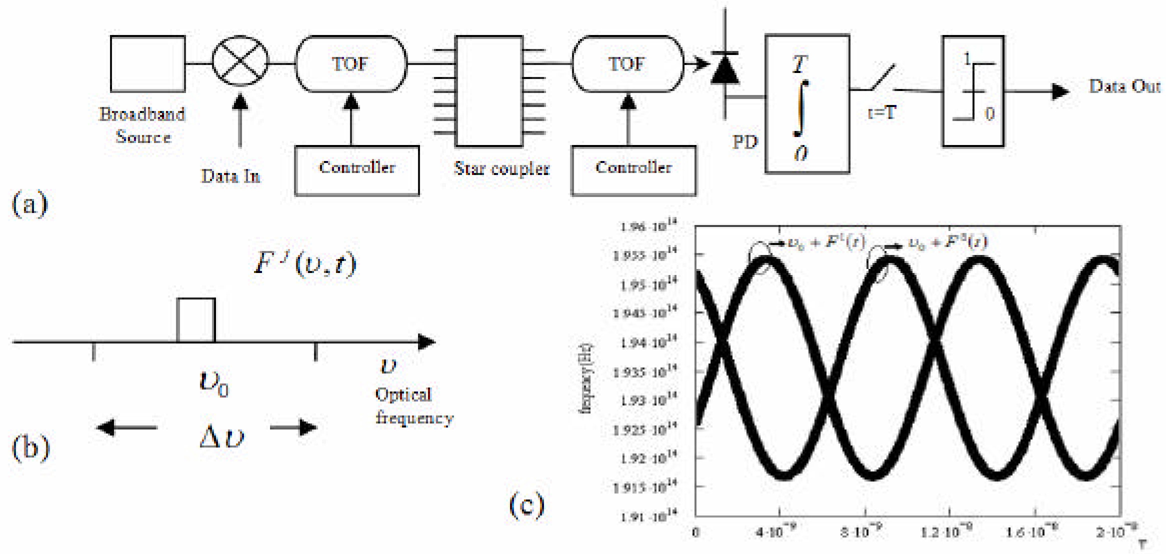


Fig. 1: (a) Block diagram of Dynamic OCDMA system. (b) Optical spectrum of a signal from one of the users. (c) Power spectral density for two users as a function of time and frequency.

The code family is given by,

$$F^{j}(t)=\frac{\Delta u}{2}\sin\left(2pft-jj\right) \tag{1}$$

where $f$ is the frequency of the functional code, and $j$ is the phase shift between different functions. Shifted sine functions are proposed for their simplicity to prove the concept and the ease of achieving the large number of codes required by reducing the phase shift. The speed of the TOF and its controller required is defined as the derivative of the code and given by,

$$S^{j}(t)=\Delta upf\sin\left(2pft-jj\right). \tag{2}$$

It is directly proportional to the frequency and amplitude of the functional code. The code construction is limited by the speed of the tunable optical filter because it determines the maximum amplitude and frequency of the code. 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 which equals to the data bit rate. Phase shift between codes ($j$) is related to the spacing between users and the code size. The phase shift for a specific code size (s) is defined as ($2p$/s). Smaller phase shift results in a family with more codes since the code will repeat itself after $2p$ radians. Reducing the phase shift will bring the users closer to each other in the spectrum. The phase shift of shifted sine code functions used in the simulation is $2p/169$, that's will give a maximum number of different codes of 169 which is same as the cardinality of MQC family of codes with $p=13$ [9], [10].

For this type of CDMA system, fast TOF will do the whole encoding and decoding by modulating the central wavelength of the filter during the bit period. One of the important features of the optical filter is the speed of tuning which is the key parameter for this application. Nanosecond tunable optical filters are available from microresonators, electrooptic, and active distributed Bragg reflector technologies [12]. The TOF in DOCDMA should be able to follow the functional code driving the filter. Other codes might be proposed to improve the system performance and relax the implementation of the system for high data bit rates.

## IV. DOCDMA PERFORMANCE ANALYSIS

In the analysis of BER we consider the effect of MAI, PIIN, and the thermal noise. Other sources, like shot noise and receiver's dark current noise are neglected and Gaussian approximation is used for the calculation of the BER.

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

$$s_{t}^{2}=(k-1)s_{DAI}^{2}+I^{2}Bt_{c}+4K_{b}T_{n}B/R_{L} \tag{3}$$

where $(K-1)s_{DAI}^{2}$ is the variance of the MAI, $I$ is the average photocurrent, $B$ is the noise-equivalent electrical bandwidth of the receiver, $t_{c}$ 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 represent the MAI effect, the second term denotes the effect of PIIN where incoherent light sources mixed at the input of the photo-detector will cause intensity variations of the output current, and the third term represents the effect of thermal noise.

The power spectral density $G(u,t)$ of the signal at the input of receiver $m$, $m\in\{1,2,..K\}$ is the sum of all active users transmitted signals,

$$G_m(u,t) = \frac{P_r}{\Delta u}\sum_{j=1}^{K} b^j rect\left(\frac{u-u_0-F^j(t)}{BW}\right) \quad (4)$$

where

$$rect\left(\frac{u-u_0}{BW}\right) = u\left(u-u_0+\frac{BW}{2}\right) - u\left(u-u_0-\frac{BW}{2}\right),$$

$u(u)$ 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,

$$G_m(u,t) = \frac{P_r}{\Delta u} b^m rect\left(\frac{u-u_0-F^m(t)}{BW}\right) + \left(\frac{P_r}{\Delta u}\sum_{j=1, j\neq m}^{K} b^j rect\left(\frac{u-u_0-F^j(t)}{BW}\right)\right) rect\left(\frac{u-u_0-F^m(t)}{BW}\right) \quad (5)$$

Then, the photocurrent is,

$$I_m(t) = \Re\int_{v=0}^{\infty} G_m(u,t)du = \Re\frac{P_r}{\Delta u} b^m BW + \Re\frac{P_r}{\Delta u}\sum_{j=1, j\neq m}^{K} b^j \sum_{i=1}^{N_{m,j}}\left(BW - \left|F^m(t) - F^j(t)\right|\right)\left(u\left(t - tL_i^{m,j}\right) - u\left(t - tH_i^{m,j}\right)\right) \quad (6)$$

where $\Re = (he)/(hu_0)$ is the responsivity of the photo-detector, here $h$ 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 $tL_i^{m,j}$ ,$tH_i^{m,j}$ are defined as the roots of the following equations respectively (see Fig. 1(c)),

$$F^m(t) - F^j(t) - BW = 0 \quad (7)$$

$$F^m(t) - F^j(t) + BW = 0 \quad (8)$$

After the integrator and sampler, the optical photocurrent is:

$$I_m = \frac{1}{T}\int_{t=0}^{T} I_m(t)dt = \Re b^m \frac{P_r}{\Delta u} BW + \Re\frac{P_r}{T\Delta u}\sum_{j=1, j\neq m}^{K} b^j \sum_{i=1}^{N_{m,j}}\left(BW(tH_i^{m,j} - tL_i^{m,j}) - \int_{L_i^{m,j}}^{tH_i^{m,j}}\left|F^j(t) - F^m(t)\right|dt\right) \quad (9)$$

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

$$I_m = b^m I + MAI(m) \quad (10)$$

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

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

where,

$$DAI(m,j) = \Re\frac{P_r}{T\Delta u}\sum_{i=1}^{N_{m,j}}\left(BW\left(tH_i^{m,j} - tL_i^{m,j}\right) - \int_{tL_i^{m,j}}^{tH_i^{m,j}}\left|F^j(t) - F^m(t)\right|dt\right) \quad (12)$$

is the interference between users $m$ and $j$,

In equation (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 $tL_i^{m,j}$ and $tH_i^{m,j}$ 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 (13) and (14) respectively,

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

$$s_{DAI}^2 = \frac{1}{K^2 - K}\sum_{m=1}^{K}\sum_{j=1, j\neq m}^{K}\left(DAI(m,j) - m_{DAI}\right)^2 \quad (14)$$

The variance of MAI can be approximated as $(k-1)s_{DAI}^2$ 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 ($t_c$), as shown in Equation (3), which is given by,

$$t_c(t) = \int_{v=0}^{\infty} G_m^2(u,t)dv \Big/ \int_{v=0}^{\infty} G_m(u,t)dv^2 \quad (15)$$

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

$$\overline{s^2_{PIIN}} = \frac{1}{K}\sum_{m=1}^{K}\frac{1}{T}\int_0^T B\Re^2 \sum_{j=1, j\neq m}^{K}\sum_{i=1}^{N_{m,j}} \left(\left(\frac{P_r}{\Delta u}b_m + \frac{P_r}{\Delta u}b_j\right)^2 \left(BW - \left|F^m(t) - F^j(t)\right|\right) + \left(\frac{P_r}{\Delta u}b\right)^2 \left|F^m(t) - F^j(t)\right|\right) \left(u\left(t - tL_i^{m,j}\right) - u\left(t - tH_i^{m,j}\right)\right)dt \quad (16)$$

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

$$SNR(k) = I^2 \Big/ \left\{(k-1)s^2_{DAI} + s^2_{PIIN} + 4K_bT_nB/R_l\right\}, \quad (16)$$

and using Gaussian approximation, the BER is given by,

$$BER(k) = (1/2)erfc\left(\sqrt{SNR(k)/2}\right) \quad (17)$$

## V. RESULTS

The BER functions for DOCDMA using sine functional code family proposed and another two SAC systems, one using Hadamard code, and the other is using MQC code with $p = 13$ [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 $\Delta u = 30\,nm$, $u_0 = 1550\,nm$, $BR = 155\,Mbps$, and filter bandwidth of $BW = 0.165\,nm$ which is equal to the chip width of SAC system using MQC with $p = 13$ and same optical bandwidth. For an error rate of $10^{-11}$, DOCDMA can accommodate up to 80 users, whereas for other systems, the maximum simultaneous users are 32 for SAC system using Hadamard code, and 52 for SAC system using MQC code. The BER of the DOCDMA 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. Indeed it is shown that the BER for DOCDMA is better than other SAC systems at any number of users of more than 50. However, for less than 50 active users, SAC system with MQC gives BER better than that of DOCDMA system. It should be noted that for this range of users, the error rate is too small (less than $10^{-14}$).

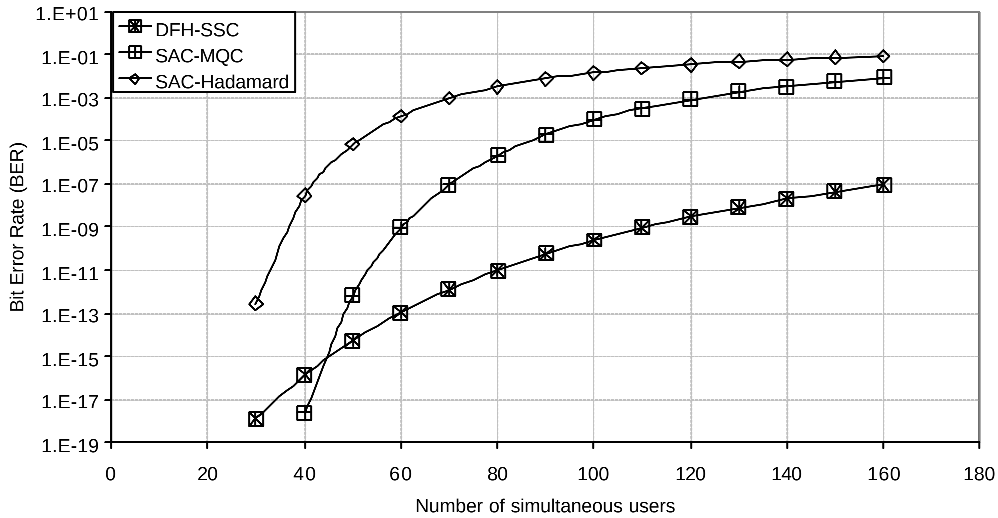


Fig. 2: Probability of error comparison between different Optical CDMA systems

## VI. CONCLUSION

We have proposed a novel low noise dynamic optical CDMA communication system. The encoder/decoder design is based on fast tunable optical filter. The filters are controlled dynamically during the data bit period. Dynamic OCDMA with sine shifted functional code family is analyzed taking into account the multiple access interference, the thermal noise, and the phase induced intensity noise. The system shows small BER at large number of simultaneous active users compared to other systems like SAC-CDMA systems using Hadamard and MQC codes.

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