Synchronous Optical Fiber Code-Division Multiple-Access Networks Using Concatenated Codes for Channel Interference Cancellation

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Abstract: The use of concatenated codes in non-coherent synchronous optical fiber CDMA networks is proposed. The concatenated code sequences are generated using balanced Walsh code sequences and Walsh code sequences. The selection of balanced Walsh code sequences is presented and the design of fully programmable transmitter and receiver is reported. The analysis of the system BER performance shows that multiple-access interference is completely eliminated and the BER performance of the proposed system is better than that of the non-coherent synchronous optical fiber CDMA system using optical orthogonal codes with double hard-limiters.

1. Introduction

In recent years, the design and analysis of non-coherent synchronous optical fiber CDMA networks have been getting much attention. So far, in the proposed systems the correlation is based on power summation and new unipolar codes such as modified prime sequence codes [1] are used. Since the correlation is based on power summation compared to the conventional bipolar codes of similar length these unipolar codes yield a lower ratio of the auto-correlation peak to the maximum value of the cross-correlation, and are therefore prone to higher multiple-access interference. This leads to a serious degradation in the bit error probability (BER) as the number of simultaneous users increases. To reduce the effect of channel interference, interference cancellation techniques have been proposed for synchronous optical fiber CDMA systems [2]-[3]. However, in those systems either multiple-access interference can not be completely eliminated or the receiver structure is relatively complex.

In this paper we propose a novel non-coherent synchronous optical fiber CDMA network using concatenated codes for achieving zero interference reception. The concatenated code sequences are generated using balanced Walsh code sequences and Walsh code sequences [4]. The selection of balanced Walsh code sequences is presented and the design of fully programmable transmitter and receiver is reported. We present the BER performance analysis and show that because the multiple-access interference is completely eliminated, the BER performance of the proposed system is better than that of the system using optical orthogonal codes with double hard-limiters described in [5].

2. Concatenated Codes

2.1 Balanced Walsh Codes

A Hadamard matrix containing all 2^n unipolar Walsh code sequences of length $N_1 = 2^n$ as its rows can be generated by the following recursive algorithm [4]:

$H_1 = [0]$

$$H_2 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \qquad H_{2m} = \begin{bmatrix} H_m & H_m \\ H_m & H^c_m \end{bmatrix}$$

where $m = 2^j$, $j \geq 1$ and the matrix H^c_m is the binary complement of the matrix H_m. According to the construction algorithm described above, any unipolar Walsh code sequence of length $N_1 = 2^n$ ($n \geq 4$) can be broken into $N_1/8$ sub-sequences of 8 chips. Furthermore, all unipolar Walsh code sequences of the same length can be grouped in two groups. The first group includes sequences formed by only one type of 8-chip sub-sequences, which is one row of H_8. The sequences of the second group are formed by two types of 8-chip sub-sequences, which are one row of H_8 and its complement.

Note that among 16 sequences of H_8 and H^c_8, except four sequences 00000000, 111 11111, 01101001 and 10010110, each of the other 12 sequences has chips "1" in symmetric positions and they can be considered as symmetric code sequences of weight $W = 4$ [6]. In this paper, those sequences are noted by G_1 = {01010101}, G_2 = {00110011}, G_3 = {01100110}, G_4 = {00001111}, G_5 = {01011010}, G_6 = {00111100} and $G^c_1, G^c_2, \ldots, G^c_6$ for their complements. The sequences $G_1, G_2, \ldots, G_6$ are named generator sequences and we call unipolar Walsh code sequences generated by those sequences and their complements *balanced Walsh code sequences.* A balanced Walsh code sequence can be represented by its generator sequence G_i and a control sequence $\{A\} = \{a_1, a_2, \ldots, a_{N1/8}\}$ where $a_j = 1$ (for $1 \leq j \leq N_1/8$) if the corresponding generator sequence is G_i and $a_j = 0$ if the corresponding generator sequence is G^c_i. A bipolar balanced Walsh code sequence can be obtained from its unipolar counterpart by mapping the elements {0,1} onto {1, -1}, respectively. The periodic cross-correlation for any pair of bipolar Walsh code sequences at zero time shift is equal zero [1].

2.2 Concatenated Codes Based on Walsh Codes

Let $\{C_i(l)\}$ and $\{D_i(j)\}$ denote periodic unipolar sequences of length N_1 and N_2, respectively ($0 \leq l \leq N_1 - 1$, $0 \leq j \leq N_2 -$

l). The bipolar forms of $\{C_i(l)\}$ and $\{D_i(j)\}$ are $\{c_i(l)\}$ and $\{d_i(j)\}$. The unipolar sequence $\{A_i(m)\}$ of length $N=N_1N_2$ $(0 \le m \le N-1)$ is a concatenated sequence made up of the inner sequence $\{C_i(l)\}$ and the outer sequence $\{D_i(j)\}$ if each "1" chip of $\{D_i(j)\}$ is encoded by another sequence $\{C_i(l)\}$ and each "0" chip of $\{D_i(j)\}$ is replaced by $\{C^c_i(l)\}$, which is the complement of $\{C_i(l\}$. Consequently, the sequence $\{a_i(m)\}$, which is the bipolar form of $\{A_i(m)\}$ is a concatenated sequence made up of the inner sequence $\{c_i(l)\}$ and the outer sequence $\{d_i(j)\}$. The periodic cross-correlation function at a zero-time shift $\theta_{a_i,a_k}(0)$ for bipolar concatenated sequences $\{a_i(m)\}$, $\{a_k(m)\}$ is [7]

$$\theta_{a_i,a_k}(0) = \theta_{c_i,c_k}(0)\theta_{d_i,d_k}(0)$$

where $\theta_{c_i,c_k}(0)$ and $\theta_{d_i,d_k}(0)$ are the periodic cross-correlation functions at zero-time shift for bipolar sequences $\{c_i(l)\}$, $\{c_k(l)\}$ and $\{d_i(l)\}$, $\{d_k(l)\}$, respectively. Since bipolar Walsh code sequences are orthogonal, if we use balanced bipolar Walsh code sequences of length $N_1 = 2^n$ as inner sequences and bipolar Walsh code sequences of length $N_2 = 2^m$ as outer sequences, the resulting bipolar balanced concatenated sequences of length $N = 2^{m+n}$ are also orthogonal.

3. Optical Transmitter and Receiver

The diagram of an electro-optical transmitter for the proposed network is shown in Figure 1. The transmitter can generate unipolar concatenated sequences with inner sequences being unipolar balanced Walsh sequences of length N_1 and outer sequences being unipolar Walsh sequences of length N_2. In the transmitter the laser generates a train of optical pulses of maximum pulse width T_c at the rate $1/T_o$ where $T_c = T/N$ is the chip duration of concatenated sequences and $T_o=N_1T_c$ is the chip duration of outer sequences. The train of optical pulses is directed to the inner encoder where optical balanced Walsh code sequences are generated. This is a parallel delay-line encoder consisting of $N_1/8$ branches providing delays $0T_c$, $8T_c$,..., $(N_1-8)T_c$ and each branch is connected to a programmable lattice, which consists of 3 tunable optical delay lines similar to that described in [8]. When a data bit "1" is transmitted, the outer sequence generator will electronically generate the outer unipolar Walsh sequence of the intended user's address sequence and forward the sequence to the inner sequence selector. Based on that sequence, the inner sequence selector will issue appropriate signals for setting lattices L_k $(k = 0,1,2,... N/8 - 1)$. Depending on whether the *k*th chip of the outer sequence is "0" or "1" the lattice L_k will be set to generate the generator sequence of the intended user's inner sequence or its complement, respectively. When there is a change from data bit "1" to "0", based on the outer sequence the inner sequence selector will generate signals for resetting each lattice allowing the inner encoder to generate the complement of the balanced Walsh code sequence. Thus, the transmitter can be programmable such that each data bit "1" is encoded by the intended user address code sequence and its complement is used for encoding bits "0". Since the network is synchronous, the generation of data bits and outer sequences as well as the generation of laser pulses are controlled by a synchronization circuit, which is not shown in Figure 1.

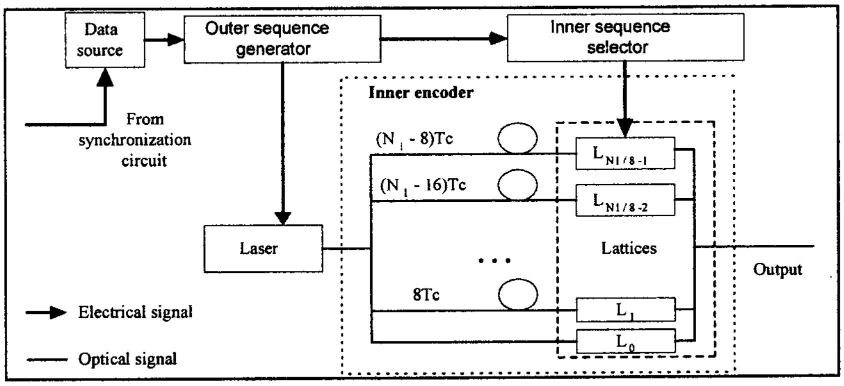

Figure 1. Transmitter for Synchronous Optical Fiber CDMA Networks

Figure 2 shows the diagram of the correlator receiver for the proposed network. The receiver consists of an inner correlator, which is a unipolar-bipolar correlator, in series with an electronic outer correlator, which performs bipolar-bipolar correlation. In this receiver, the received optical signal is directed to the inner correlator, where it is split into $N_1/8$ parts by a $1x(N_1/8)$ splitter. The outputs of the splitter are connected to optical delay-lines, which provide delays of $0T_c$, $8T_c$, $16T_c$,..., $(N_1 -8)$ T_c. The output of each delay line is split into two parts by an $1x2$ splitter and the outputs of the *k*th $1x2$ splitter $(k = 0,1,2,... N_1/8 - 1)$ are connected to two programmable lattices L_{ka} and L_{kb}, which are similar to that used in the transmitter. The lattices L_{ka} and L_{kb} are set to the *k*th generator sequence of the receiver's inner sequence and its complement, respectively. Depending on whether the *k*th chip of the receiver's outer sequence is "0" or "1" the output of lattice L_{ka} is connected to the $(N_1/8)x1$ combiner C_1 or the $(N_1/8)x1$ combiner C_2, respectively. The output of lattice L_{kb} is connected to the remaining combiner. Therefore, the inner correlator consists of two unipolar-unipolar correlators: That of output C_1 correlates the received signal to the receiver's inner sequence and the other correlates the received signal to the complement of the receiver's inner sequence. The optical outputs of these correlators are converted into electrical currents and subtracted in a pair of balanced photodiodes. The resulting signal, which is the bipolar correlation of the received signal to the inner bipolar Walsh code sequence of the user address sequence is then correlated to the outer bipolar Walsh sequence of the user address sequence, which is electronically generated by the outer sequence generator. Data is recovered by sampling at the auto-correlation peak and zero-threshold detection. The generation of the outer sequence and the sampling time are determined by a synchronization circuit, which is not show in Figure 2. In this receiver, by using the inner sequence selector, and the outer sequence generator different concatenated address code sequences can be selected. Hence, the receiver is also programmable.

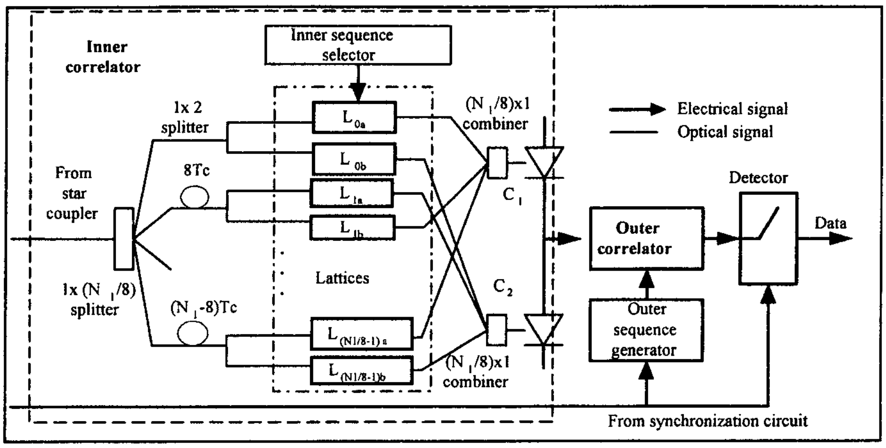

Figure 2. Receiver for Synchronous Optical Fiber CDMA Networks

4. BER Performance

We investigate a network with K simultaneous transmitters, which are synchronized to each other. Assume that the received chip optical power for all transmitter at a given receiver is P. The total received optical signal $R_i(t)$ at the input of the ith receiver is the incoherent sum:

$$R_i(t)=\sum_{k=1}^{K}P[B'_k(t)A'_k(t)+B'^c_k(t_k)A'^c_k(t)]$$

where $A'_k(t)$ and $A'^c_k(t)$ are the code waveform of the intended receiver and its complement transmitted by the kth user, $B'_k(t)$, $B'^c_k(t)$ are the transmitted binary signal and its complement, respectively. The waveform $A'_k(t)$ consists of a unipolar concatenated sequence of length N constructed from the inner unipolar balanced Walsh sequence $C'_k(t)$ of length N_1 and the outer unipolar Walsh sequence $D'_k(t)$ of length N_2. At the inner correlator the received signal is split into two equal parts and the correlator of output C_1 correlates it to the unipolar inner address sequence $C'_i(t)$ while the other correlator correlates the received signal to the complement $C'^c_i(t)$ of $C'_i(t)$. The correlator output signals are converted into electrical currents in a pair of balanced avalanche photodiodes (APD) of responsivity R *(A/W)* (at unit gain) and APD gain M. At the outer correlator the resulting electrical signal is electronically correlated to the bipolar outer address sequence $d'_i(t)$. The current $i_i(t)$ at the output of the outer correlator at time $t=T$ can be written as

$$i_i(T)=\frac{RMP}{2S}\frac{1}{T_o}\int_0^T\left\{\frac{1}{T_c}\sum_{k=1}^{K}\int_0^{T_o}[B'_k(t)A'_k(t)+B'^c_k(t)A'^c_k(t)]\right.$$
$$\left.\cdot[C'_i(t)-C'^c_i(t)]dt\right\}d'_i(t)dt+\int_0^T n(t)dt. \qquad (1)$$

where S is the optical loss factor of each unipolar-unipolar correlator. The last term of (1) is the total noise current composed of shot noise and thermal noise due to both photodiodes and the outer electronic correlator.

For $1 \le k \le K$, the relationship between the sequences $A'_k(t)$, $C'_i(t)$ and their bipolar version $a'_k(t)$, $c'_i(t)$, the data signal $B'_k(t)$ and its bipolar form $b'_k(t)$, leads to the identities

$$[B'_k(t)A'_k(t)+B'^c_k(t)A'^c_k(t)]=\frac{[1+b'_k(t)a'_k(t)]}{2} \qquad (2)$$

$$C'_i(t)-C'^c_i(t)=c'_i(t). \qquad (3)$$

Substituting (2), (3) into (1) and since the inner bipolar Walsh code sequences are balanced we get

$$i_i(T)=i_{(i,i)}(T)+\sum_{k=2}^{K}i_{(i,k)}(T)+\eta$$

where η is equal to the last term in (1) and

$$i_{(i,i)}(T)=\frac{RMP}{4S}b_i(0)N \qquad (4)$$

$$i_{(i,k)}(T)=\frac{RMP}{4S}\frac{1}{T_c}\int_0^T b'_k(t)a'_k(t)a'_i(t)dt=\frac{RMP}{4S}b_k(0)\theta_{a_i,a_k}(0) \qquad (5)$$

where $b_i(0) \in \{1, -1\}$ is the bipolar data bit transmitted to the ith user, $b_k(0) \in \{1, -1\}$ is the bipolar data bit transmitted by the kth user and $\theta_{ai,ak}(0)$ is the periodic cross-correlation at zero-time shift for two bipolar concatenated code sequences $\{a_i(m)\}$ and $\{a_k(m)\}$. Equation (4) shows the desired signal and equation (5) represents the multiple-access interference (MAI) caused by the kth user at the receiver of the ith user. Since the periodic cross-correlation at zero time shift of any pair of bipolar concatenated code sequences generated using Walsh code sequences is equal zero then the MAI is zero. Therefore, the BER performance of the system does not depend on the MAI but only on the shot noise and thermal noise. By assuming all the noise processes to be independent and approximate the shot noise in each photodiode by Gaussian statistics and model the thermal noise as a Gaussian random process, the total noise power is calculated by

$$\sigma_N^2 = 4qBM^2F_A(\frac{KRPN_1}{16S} + i_D) + \frac{4k_BT_TB}{R_L}.$$

where q is the electric charge, i_D is the dark current, B is the noise-equivalent receiver bandwidth, F_A is the excess noise factor of the APD, k_B is the Boltzmann's constant, T_T is the receiver noise temperature and R_L is the receiver load resistor. Finally, the bit-error rate can be calculated by

$$BER = \frac{1}{2}erfc[\frac{RMPN}{8S\sqrt{2qBM^2F_A(\frac{KRPN_1}{16S} + i_D) + \frac{2k_BT_TB}{R_L})}}].$$

where *efrc (x)* is the complementary error function.

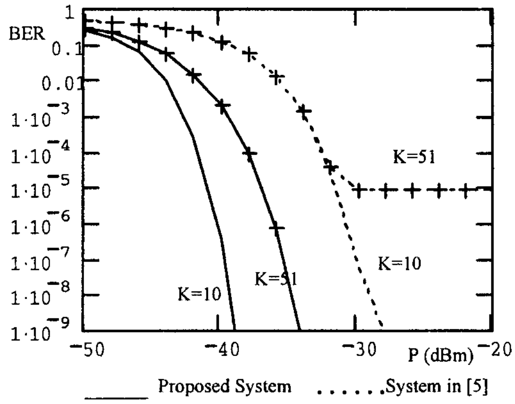

Figure 3. BER Performance of Two Systems

We compare the performance of the proposed system with that of the non-coherent synchronous optical fiber CDMA system using optical orthogonal codes (OOCs), where parallel delay line receiver with double hard-limiters and APD are employed [5]. In our calculations we use the same parameters as those in [5]. The BER performance is calculated as a function of the received chip optical power $P \in$ (-50 dBm, -20 dBm). Concatenated code sequences of length N=1024, with inner balanced Walsh code sequences of length N_1=32 and outer Walsh code sequences of length N_2=32 are used for the proposed system while OOCs of length N=1023 and weight W=5 are used for the system described in [5]. For N=1023 and W=5 the maximum number of available OOC sequences is 51 [5] while there are 768 concatenated sequences. The laser pulse width T_c=0.03 ns is used for both systems, hence, they operate at a data bit rate of about 32.5 Mb/s. We found that for a BER=10^{-9} the maximum number of simultaneous user is 10 for the system described in [5] and 51 for the proposed system. The BER for two systems is shown in Figure 3. It can be seen that for a BER=10^{-9} and K= 10 the proposed system requires a chip optical power of –39 dBm while for the system described in [5] a higher chip optical power of -28 dBm is required. For K= 51, the proposed system still can achieve BER= 10^{-9} with a received chip optical power of – 34 dBm while the BER of its counterpart is limited at BER = 10^{-5} and the degradation of the BER can not be overcome even for arbitrary high received optical power. The better performance of the proposed system is due to the fact that the MAI is completely eliminated by the use of Walsh code sequences and unipolar-bipolar correlation.

5. Conclusions

This paper proposes the use of Walsh codes sequences to generate concatenated code sequences for non-coherent synchronous optical fiber CDMA networks. The design of fully programmable transmitter and receiver is reported. We present the system BER performance analysis and prove that multiple-access interference is completely removed. Therefore, a large number of users can simultaneously transmit and very high throughput can be achieved. The BER performance of the proposed system is also compared to that of the non-coherent synchronous optical fiber CDMA system using OOC sequences and double hard-limiters [5]. We show that the BER performance of the proposed system is better than that of its counterpart and it can support a larger number of potential subscribers. Hence, the proposed scheme is particularly attractive for future high capacity optical fiber networks.

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